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The Electromotive Force

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SOMEHOW the word spontaneous is associated in our minds with the idea of positiveness. Because the electromotive force can be used as a criterion of the tendency of a process to take place, the physical scientist assigns a positive sign to the electromotive force of those processes that proceed spontaneously when existing restraints are removed. It is really the use of the electromotive force as a criterion of the possibility of the occurrence of a process that renders the concept of greatest importance.

The electromotive force belongs to the class of intensive or potential properties, being independent of the quantity of material consumed or produced in a process. The nature of the electromotive force must, therefore, be clearly distinguished from that of a mechanical force, which is proportional to the mass of the body involved.

SPONTANEOUS PROCESSES

The very existence of a positive electromotive force, or a positive tendency for any given process to take place, implies that there must also exist a barrier to the completion of the process. If this were not so, then the electrical machine would run down, as when a secondary battery is short-circuited, an automobile tire punctured, or a dam swept away by a sudden failure of the masonry.

The chemist expresses processes in the form of equations. He writes on the left side of the equation the amount, kind, and condition of the substances that disappear, and on the right, the amount, kind, and condition of the substances that appear. He is thus able to formulate the simplest or the most complicated processes. For example, he writes the reaction for the discharge of the lead secondary cell,

$$Pb(s)+PbO_2(s)+2H_2SO_4(aq) = 2PbSO_4(s)+H_2O \text{ (in } H_2SO_4); \quad (1)$$

for the leakage of compressed oxygen from a storage tank,

$$200 \text{ ft}^3 \text{ S.T.P. } O_2 \text{ } (g, 150 \text{ atmos}) = 200 \text{ ft}^3 \text{ S.T.P. } O_2 \text{ } (g, 1 \text{ atmos}); \quad (2)$$

or for the filling of an elevated storage reservoir at average head h,

$$5000 \text{ gal } H_2O \text{ (head} = 0) = 5000 \text{ gal } H_2O \text{ (head} = h). \quad (3)$$

If the reaction or process as written is spontaneous in one direction when a positive electromotive force is conventionally assumed, then when the process or reaction takes place in the reverse direction (the substance disappearing remaining in the left-hand member of the equation) it can no longer be spontaneous. The concept of a negative electromotive force, therefore, implies that work must be done on the system or that some other spontaneous process must take place, which, when combined with the desired process, will render the combined system capable of spontaneous completion.

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Thus, when the secondary cell reaction of Eq. (1) is reversed and the cell charged, energy is supplied from an outside source. When the oxygen tank of Eq. (2) is refilled, work is done on the compressor. The reaction or process of Eq. (3) is not spontaneous, but requires work supplied to the pump which raises the water from zero head to head h.

Reversible Electromotive Force

If there is no tendency for a process to occur in either direction when any existing barriers to the completion of the reaction or process are removed, then the electromotive force of the process is zero. Thus, if a counter electromotive force or potential just equal to that of the secondary cell is supplied, there will be no tendency for the process of the combined system to occur; no current will exist when the combined system is short-circuited through a galvanometer. If the applied counter electromotive force is infinitesimally less than the electromotive force of the cell, then a very small, but nevertheless actual, amount of electricity will flow through the galvanometer and a small amount of lead, lead peroxide, and sulfuric acid will disappear. On the other hand, if the applied counter electromotive force is very slightly greater than the electromotive force of the lead storage cell, electricity will flow in the reverse direction through the galvanometer and lead, lead peroxide, and sulfuric acid will appear.

In like manner, when the oxygen tank is attached to a storage tank containing oxygen, in which the pressure is just equal to that in the oxygen tank, gas will not flow in either direction. If the pressure in the auxiliary tank is slightly less, gas will flow slowly from the oxygen tank, and when the pressure in the auxiliary tank is slightly greater, oxygen will flow into the oxygen tank. Such reactions in balance, are *reversible*.

The Activity Quotient and the Standard Process

If we write for a generalized process at constant temperature,

$$lL+mM+nE^{-}+\cdots=rR+sS+\cdots, \quad (4)$$

then, by the application of the laws of thermodynamics,[2] we find that

$$\mathbf{E}=\mathbf{E}^{\circ}-(\mathbf{R}T/n\mathbf{F})\ \ln Q, \quad (5)$$

where $\mathbf{E}$ is the electromotive force, $\mathbf{E}^{\circ}$ the standard electromotive force, $\mathbf{R}$ the gas constant, T the absolute temperature, $\mathbf{F}$ the Faraday equivalent, and ln Q the natural logarithm of the activity quotient. The activity quotient is arbitrarily written as

$$Q=a_R{}^r a_S{}^s\cdots/a_L{}^l a_M{}^m\cdots, \quad (6)$$

where a is the activity of the several substances taking part in the process. We note that the substances appearing occur in the numerator, and that the activity of each substance is raised to the power corresponding to the number of mols of that substance as written in Eq. (4). When the quotient Q is unity then the electromotive force is numerically equal to the standard electromotive force. The standard electromotive force is, therefore, numerically dependent upon the choice of units of activity.

For pure solids or liquids, at one atmosphere pressure, the activity is taken to be unity. For solvents the activity is approximately equal to their mol fractions, for gases to their partial pressures in atmospheres, and for solutes to their mol fractions or to their molalities (mols per 1000 gm of water in vacuum). Because of the individual characteristics of the several substances, it is usual to multiply by an activity coefficient in each case, but for approximate uses this is unnecessary.[2]

The condition of equilibrium is characterized by lack of tendency of the process to occur spontaneously in either direction. The electromotive force at equilibrium is, therefore, zero and, by Eq. (5), the last term is numerically equal to the standard electromotive force. For this special value of the activity quotient we reserve the name *equilibrium constant*, which we designate by the symbol K.

The Escaping Tendency

When a substance tends to move spontaneously from one phase to another, or from one portion of a phase to another portion of a phase,

[2] See, for example, Lewis and Randall, *Thermodynamics and the Free Energy of Chemical Reactions* (McGraw-Hill, 1923).

it is said to possess a higher escaping tendency, or higher fugacity. In case the escaping tendency is the same in all the phases which are in contact, there is no net tendency of the substance to move from one phase to another. Thus, in a solution of sugar in water at its freezing point under its own vapor pressure and with a constant heat content, there is no net gain in the amount of water in the solution or in the vapor or in the solid ice phase. We may use the vapor pressure of a constituent as a measure of its escaping tendency, or fugacity.[2] Just as there is a very small, but nevertheless real, partial pressure of sugar in the vapor phase, there is also a slight solubility of sugar in the solid ice, sufficient for the fugacity of the sugar to be the same as in the liquid phase.

The fugacity of the electron in two phases will likewise be the same when there is no tendency of the electron to escape from the one phase to the other. If the pressure of fluid at one end of a tube is made greater than at the other, the fluid will tend to flow so as to increase the pressure at the low pressure end and decrease the pressure at the high pressure end of the tube. The rate of flow will depend upon the difference in pressure and inversely upon the resistance to flow. So, if the potential, or the escaping tendency of electrons, is made greater at one end of a conductor, the electrons will tend to flow from the place of higher to the place of lower escaping tendency. The current will depend upon the difference in fugacity of the electrons and upon the conductivity of the conductors. Since, in the secondary cell short-circuited through a galvanometer and with an equal counter electromotive force there is no current, and therefore no movement of electrons, we may conclude either that the escaping tendency of the electron is the same throughout the whole circuit or that a difference in fugacity of the electron in one part is exactly balanced by differences in some other part or parts of the circuit.

A metal such as silver, when isolated, partially dissociates into solid silver ion and electron; that is,

$$Ag(s) = Ag^{+}(s) + E^{-}. \qquad (7)$$

Hence, in accordance with the law of mass action, if electrons are withdrawn the silver becomes positively charged and some of the undissociated silver will further dissociate to produce more solid silver ion and electron. When a piece of silver is placed in a silver nitrate solution the system remains electrically neutral, from which we must conclude that the escaping tendency of silver ion in the metal and in the solution is the same and that the escaping tendency of electrons in the silver and in the solution is also the same. Likewise, the escaping tendency of the silver ion and electron in the gas phase above the solution must be equal to that in the solid and liquid phases.

We may define *a mol of electricity* as that amount of electricity which combines with 1 gram atom of chlorine to form 1 mol of chloride ion. If a solution of silver nitrate is placed in a vessel containing silver electrodes, 0.001118 gm of silver will be deposited upon the cathode, and the same amount of silver will be dissolved from the anode for each coulomb of electricity which passes. One mol of electricity, or 96 494 coulombs, will deposit or dissolve 1 mol of silver. This number is the *Faraday equivalent*, and represents the quantity of electricity contained in 1 mol of electricity. It requires the addition of $2 \times 96\,494$ coulombs, or 2 Faradays, to deposit 1 mol of copper from 1 mol of cupric ion. If we represent the mol of electricity by the symbol E^{-}, we may express this result by the chemical equation

$$Cu^{++} + 2E^{-} = Cu(s). \qquad (8)$$

If both electrodes are made of copper, 2 mols of electricity and 1 mol of cupric ion will be formed by the solution of 1 mol of copper at the anode. Expressed as an equation, we have,

$$Cu(s) = Cu^{++} + 2E^{-}. \qquad (9)$$

On adding Eqs. (8) and (9) we find that the net effect is the transference of 1 mol of copper from the anode to the cathode by the passage of *2 mols*, or, as it is sometimes expressed, by the passage of *2 equivalents* of electricity.

Half-Cells

When we measure the reversible electromotive force of a cell we must of necessity have a steady state within the cell. We divide an electrolytic cell into two half-cells, in one of which—the cathode—the electron disappears, and in the

other—the anode—the electron appears. We need not go into the mechanics of writing the equations of such half-cells further than to indicate that Eqs. (8) and (9) are representative of those involved. This division into half-cells represents the process that occurs at the respective electrodes, but when we come to apply Eq. (5) we must make some sort of an arbitrary choice. This arbitrary numerical convention is to assume the electromotive force of the half-cell to be described by the equation

$$\tfrac{1}{2}H_2(g,\ a=1)=H^+(a=1)+E^-;\ \mathbf{E}=0. \quad (10)$$

This does not imply that the electromotive force of this half-cell is actually zero when the reactants are in their standard states, or at unit activities, but rather that when some half-cell is combined with a hydrogen electrode at unit activities, the measured electromotive force is taken as the electromotive force of the given half-cell. Otherwise, Eq. (5) is applicable to half-cells as well as to entire cells.

The Seat of Electromotive Force in a Cell

The difference in activity or fugacity of the substance, *electron*, at the metallic terminals of a cell has a definite value which may be thought of as measured by the difference in potential. Since the contents of each half-cell must in themselves be in equilibrium in order to measure the reversible electromotive force, there cannot be any difference in the escaping tendency or fugacity of any of the constituents, including electron, in either half-cell. There must therefore, exist a difference in the activity of electron across the barrier (mechanical, chemical, or otherwise) that exists between the two half-cells. This difference in fugacity of the electron, in the absence of a finite current, must just equal the difference in fugacity of the electron between the metallic terminals of the cell. This statement cannot be otherwise. If the reversible electromotive force of the cell is positive, then there must be some sort of a barrier to the establishment of an equilibrium between the contents of the two half-cells. For if the contents of the two half-cells are mixed, a reaction will proceed until chemical equilibrium is obtained. Under these conditions at equilibrium, the process no longer proceeds spontaneously and therefore no positive electromotive force can exist. Of the various substances making up cells, the electron possesses immeasurably greater mobility than either solid, liquid, or gaseous uncharged particles or ions. Of all the substances therefore, which are placed in a half-cell at balance, we may say that the electron is the one which possesses an identical escaping tendency at all points in the half-cell.

We have suggested that equilibrium must exist in each half-cell; otherwise no reversible electromotive force can be measured. In every known electrolytic cell there is a difference in the character of the solution in contact with the electrode known as a cathode and in contact with the electrode known as the anode. When the contact between the two halves of the cells is made by means of the electrolyte (sulfuric acid in the case of the lead storage cell) there is a diffusion gradient of dissolved lead peroxide in the sulfuric acid in immediate contact with the solid lead peroxide towards the lead electrode. There is also a diffusion gradient of dissolved lead in equilibrium with solid lead at that electrode, towards the opposite electrode in the intermediate region. This dissolved lead peroxide and lead diffuses and reacts very slowly to form lead sulfate, thus producing an effect that tends to short-circuit the cell internally. In practice we insert a wooden or rubber perforated separator to prevent as far as possible the acceleration of this process through mechanical mixing of the anode and cathode solutions.

In the more usual cases, for example when a calomel electrode is used in a cell without liquid junctions (it is not our purpose to discuss the mechanism of liquid junctions), the length and small diameter of the connecting tubing is sufficient to furnish a complete barrier to the mixing of the anode and cathode solutions. In the well-known Daniell cell, advantage is taken of the difference in density of the anode and cathode solutions to prevent their mixing and internally short-circuiting the cell. It is obvious that an internal short circuit is equivalent to allowing the process of the cell to run to completion without performing any useful work.

The barrier to the completion of the process may be chemical as well as mechanical; for example, if hydrogen ion reacts with an electron at a bright platinum or mercury surface atomic

hydrogen is produced. If the cell were completely saturated with atomic hydrogen at a definite activity or partial pressure, then we could measure a definite potential or electromotive force of the cell, for the process in which this atomic hydrogen of a definite activity is taking part. If now we provide the electrode with a platinum black surface which possesses the property of catalyzing the reaction of atomic hydrogen to form ordinary hydrogen gas, and if the catalyst is sufficiently active, we may regard the process in the cell as one which occurs in such a way that hydrogen gas of a definite activity takes part. This is the explanation of the so-called phenomena of overvoltage at a metallic electrode.

Another interesting cell is one containing what is known as a polonium electrode. A silver-silver chloride half-cell forms one electrode, the other being the surface of the hydrochloric acid with a metallic plate placed close to it but not in contact with the surface. The gas space between the electrode and the surface is ionized by means of α-rays from polonium. Thus hydrogen ions react with gaseous ions at the surface to produce atomic hydrogen of a more or less definite activity, depending upon how fast the atomic hydrogen diffuses away from the surface. Obviously the potential of such a cell is independent of the character of the gas being ionized by the polonium. While it is impossible to obtain an entirely reproducible electromotive force from such a cell, it corresponds in its relation to Eq. (5) to the process which I have suggested.

SUMMARY

In this paper I have treated the electromotive force from the standpoint of its use as a criterion of the tendency of a process to take place. I have also shown that it is impossible for an electromotive force to exist without some sort of a mechanical, chemical, or diffusional barrier to the establishment of equilibrium in the process. This barrier is responsible for the existence of the measurable electromotive force. The ability to make reproducible measurements of electromotive force depends primarily upon the ability to obtain equilibrium at the electrodes of electrolytic half-cells and to obtain a reproducible, steady state "leakage," or breakdown of the barrier to the attainment of equilibrium in the process. Unless a definite process can be formulated for the potential or electromotive force in question, the interpretations based upon these potentials must, of necessity, be uncertain.

The Teaching of Intermediate Physics

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I

IT is generally conceded that the successful teacher of physics must possess two qualities: knowledge of his subject and pedagogic skill. If he is at the same time a researcher in a special field he is likely to bring to his classroom a singularly communicative enthusiasm which enhances his success as an instructor. All this has been fully recognized, and attention has generally been directed to the means whereby these considerations can be rendered more effective in the teaching of physics.

The question we wish to ask, and attempt to answer in the present discussion, is whether these standard qualities, which are admittedly necessary, are also sufficient for meeting the demands that confront the teacher of physics at present. To anticipate the answer, we shall take the unpopular stand that he also needs some knowledge of philosophy, and a considerable faculty for philosophic circumspection.

Knowledge of the subject and pedagogic skill suffice to teach a subject that is closed, in which no further advances, no revolutions of thought, are likely to occur. Physics taught as knowledge even with the utmost pedagogic skill remains a sterile acquisition, giving rise at most to disillusionment and perhaps contempt when the

pupil awakens to the fact that part of his knowledge is contradicted by later developments in the subject. It is the *spirit* of physics with which a student is to come in contact, and this spirit of physics is not as easy to communicate as are facts. Indeed it is not even easy to define succinctly.

Its correct comprehension—and no teacher of physics should fail in this comprehension—comes only when we attempt to understand the ultimate object of physical science. For it is this ultimate object which remains invariable in the midst of shifting interests and research fashions, and which orders and alters physical knowledge. Let us then first try to see what this object is.

Sometimes physics is said to have as its ultimate aim the exploration of the universe in the sense of an accumulation of data of a certain type, or of all the "facts regarding matter and energy." This attitude, we believe, fails to describe the *central* meaning of the science and does not catch its spirit. The distinctive character of scientific systematization does not exhaust itself in mere classification of facts. The existence of physical theories that go beyond facts and, indeed, permit new predictions, is ample proof for the inadequacy of the view that regards physics as a mere aggregation of data.

Some textbooks claim that the object of physics is the gratification of an innate curiosity about the world. This curiosity makes us wonder what will happen if certain manipulations are carried out on certain objects, and the test is then put to nature. It is clearly true that many advances in the field of experimental physics are accomplished in precisely that way, but it appears that the status of theoretical physics is not quite properly described as the result of a mere curiosity about the world. For, would physicists be satisfied if all perceptible workings of nature were known, or would they still inquire into subtle, imperceptible relations between these facts? I believe that the latter would be the case. We are already approaching dangerously close to philosophic issues.

The assertion that physics springs entirely from the virile urge to dominate nature is not difficult to refute. To be sure, this urge may be the motivating power in the minds of some, not many, technically minded students, but it is not the perennial source of physical investigations. The texture of modern theories is far more delicate than such a view would permit, and many of them, beautiful with internal grace and mathematical elegance, will never promote our domination of the universe. Yet they are as integral a part of physics as, for example, the study of the strengths of materials.

Next we come to the view, widely held at present, which identifies the object of physical investigation with the acquisition of facilities to predict. It cannot be denied that physics provides such facilities in an ever increasing measure and that its practical value largely resides therein. But is not this advantage rather a by-product than the sole end of research? Scientific knowledge is power and will forever be power; nevertheless, there are many who claim that they would pursue their scientific endeavors even if this were not true. The pursuit of physics gives them pleasure, and this pleasure is not peculiar to the act of prediction; it is present whenever a problem is solved. Thus it seems, at least from a psychological point of view, that the driving force in physical investigations cannot be exclusively the fun or the profit of prediction.

Then, too, there are numerous physical theories which, thus far, have failed to make any noteworthy predictions. The value of physical theories is clearly not fixed in proportion with this particular merit. Nor does a physical theory lose its value when its range of application is almost closed and it is hardly in a position to enable further predictions. The misconception that scientific research be essentially a matter of predicting new phenomena has produced a most insidious practice not altogether uncommon among contemporary physicists. The scheme is to publish, from time to time, a sufficient number of predictions without giving detailed reasons for them, so that at least a few of them will come true by the laws of chance. Since valid predictions are very impressive and the memory of blunders tends to fade away, this scheme is sometimes regarded as a vehicle to fame.

Evidently the physicist's business involves something more than prophecy, something that makes his experience peculiarly coherent and produces an internal fitness which facility for

prediction alone does not convey. It is at this point that philosophy enters. It emerges the moment we endeavor to state the object of physics: paradoxically enough, physical explanation is essentially a metaphysical process.

Space does not permit a full exposition of the metaphysical character of the methods of inquiry used in physics. This has been done elsewhere.[1] Suffice it to say here that the object of physics is to set up a correspondence between sense data—which in themselves lack the coherence with which our mind wishes to endow experience—and a field of symbolic constructs that are subject to arbitrary but clearly statable rules of combination. The full course of physical explanation begins in the range of perceptible awareness, swings over into the field of symbolic construction, and returns to perceptible awareness. The field of symbolic construction is populated with many entities like atoms, electrons, electromotive forces, etc., some of which are themselves unobservable and whose properties are partly assigned by *metaphysical* rather than *physical* considerations (simplicity, noncontradiction, etc.).

But what is the connection between all this and the teaching of intermediate physics? The link is evident on realizing that these matters, which by their very nature are suitable for incorporation in intermediate physics courses, have been almost always omitted. Is this because they have no psychological appeal to college students? Experience has led me to deny this question.

II

It may be of some interest in this connection to analyze the various types of psychological appeal of which physics is capable, and to see in what ways they have been utilized in the teaching of the subject.

The interest most commonly recognized by educators, and captured by standard physics courses, is of the technical sort. Students of a manipulative bend are naturally drawn toward a subject that emphasizes nicety and precision in the handling of tools and apparatus. Much is being done and should be done to foster this type of interest. Pedagogs are generally aware of the desirability of steps in this direction, so it is hardly necessary to dwell upon this matter here.

The second appeal which draws a distinct group of students into physics is the analytic one. Usually the man with propensities for analysis and a keen eye for logical detail goes into pure mathematics, but it often happens that he is repelled by the abstractness or lack of concrete applicability of the developments in that field and turns then to physics. Much, though perhaps not enough, is done in intermediate courses to utilize this type of interest, for the good teacher will make his presentation mathematically and logically consistent, and thereby endeavor to satisfy the student in this category.

I feel that these two are the only types of appeal that are promoted through our present methods of teaching intermediate physics. To be sure, one often speaks of a "general" interest in physics, and seeks to take advantage of it by making the subject easier through diffusion and loose talk, or by the introduction of spectacular and startling demonstrations, or by giving superficial emphasis to modern physics. Fortunately these attempts at embellishment are mainly limited to elementary courses where probably they do no harm. But the tendency of capturing an unqualified "general" interest in the subject is almost certainly based on a misconception because the existence of general interest is a myth. When a student professes general interest in the subject of physics he is usually in ignorance as to his own inclinations. It seems doubtful whether the interest of such a student could be held even if deliberate attempts were made to popularize the instruction, unless the subject had genuine *specific* appeals for him, of which he was initially not cognizant.

There is, however, a third type of appeal which could well be utilized and promoted with profit to the physical profession. It is the philosophic appeal of physics. In maintaining this point before physicist readers three things are necessary: first, to remove the common supposition that philosophy is harmful to the precision of physical thought; second, to show that philosophic interest is widespread and alive among students; finally, to make sure that physics contains many elements to which the philosophic

[1] H. Margenau, J. Phil. Sci. 2, 48 (1935).

taste is sensitive. The first of these is the most difficult task and will not be attempted here. We only remark that the aversion of physicists to philosophy, a localized phenomenon rather typical of Western physics, is no longer as severe as it has been in the past and that there are signs of an impending fraternity between these subjects. The fact that philosophic interest is universal needs little elaboration; the misfortune to physics is that this interest had to feed largely on theology and unauthentic science instead of being groomed and harnessed for the benefit of the exact sciences.

III

The preceding considerations are of particular importance with regard to the teaching of intermediate physics, where students are usually alert to the larger settings of special physical problems, and yet not sufficiently advanced to carry on research. At present, intermediate physics is a badly neglected field. Statistics show that, while the number of college students taking elementary courses in chemistry is three times as great as the corresponding number in physics, chemistry has eight times as many majors as physics, thus indicating a strong relative decrease in the enrolment in intermediate physics courses. Yet there are few proposals for reform. The methods used are often antiquated and the instruction, uninspired. The reason for the latter fact is not far to seek; the research man often teaches undergraduates grudgingly and considers his work a burden, while the elementary teacher is sometimes unsuited for intermediate instruction.

To improve this situation the proposal is here made that physicists avail themselves more effectively of the hidden possibilities that lie in philosophic interpretation. Students do respond so readily to attempts to uncover obscure relations. In my experience much more discussion arises on the part of students during an inquiry into the logical meaning of Newton's laws, or a critical analysis of Newton's definition of force and mass, than during the mathematical development of these laws. Helmholtz' attempt to *prove* the principle of conservation of energy and the conditions for this proof have always occasioned more comment than an exposition of the principle itself or its innumerable applications. The same manifestation of interest occurs when Hamilton's or Fermat's principles are analyzed from the point of view of teleology and contrasted with the apparently causal view expressed in the differential equations of mechanics.

IV

At Yale University, an intermediate course in which these principles are utilized has been taught for a number of years. Since its contents might seem of interest in view of the present suggestion, I shall take the liberty of describing them briefly. The course is entitled "Foundations of Modern Physics" and is open to juniors and seniors. Graduate students frequently audit the work. The first semester covers fields of physics, like atomic structure and radioactivity, in which the most fundamental advances of the last generation have taken place. The second part starts with a survey of the history of physical thought and then proceeds with a logical and mathematical development of some important physical theories; such as, the statistical theory of gases, the meaning and validity of conservation principles, the meaning of probability and its application to physical reasoning, relativity theory, and some quantum mechanics. It includes the analysis of basic concepts like time, space, continuity, and causality. The work is done in lectures which are interrupted at frequent intervals by seminar reports in which the students present the results of their reading. It is a pleasure to say that we have enjoyed the cooperation of some members of the philosophy department in this work.

The suggestion here made is not entirely without danger. It cannot be carried out by physicists who have neither philosophic interests nor information. The attempt might lead to a dilution of physical knowledge rather than to its intensification. It might repel students rather than attract them. One cannot, therefore, make the proposal without at the same time advocating the dissemination of sound philosophic information among teachers of physics.

Spectroscopy—A Survey

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ONE of the most interesting examples of the agreement between theory and experiment in modern physics occurs in the structure of the atom as revealed by atomic spectra. The experimenter, on one hand, goes into the laboratory where, on a photographic plate, he takes a picture of the lines due to the varicolored light from a particular type of atom. From these lines on the plate, he is then able to determine the energies of the different stationary states of the atom. The theorist, on the other hand, sits at his desk; and, beginning with Coulomb's law and applying quantum mechanics, gradually develops a conception of the structure of the atom from which, with the aid of considerable mathematics, he finally is able to calculate these very same atomic energies. The fact that, in some cases, the results agree to within the experimental errors shows that the ideas thus developed must describe fairly closely the structure of the atoms existing in nature. First the experimental and then the theoretical method of finding atomic energies will be described.

The experiments involve several distinct processes: (a) the atoms must be excited to produce light of different wave-lengths; (b) this light must be separated into these wave-lengths—dispersed—and the resulting spectrum photographed; (c) the photographic plates must be measured and the wave numbers of the lines—the number of waves per centimeter—found; and (d) the energy levels of the atom must be determined from the wave numbers of the lines.

Sources

Turning first to the sources of light, we find four commonly in use: the discharge tube, the electric arc, the electric spark, and King's furnace.

(*1*) *The discharge tube.*—A common type of electric discharge is that in a Geissler tube, which consists of two electrodes in a glass tube at an appropriate low pressure. There are two properties of a discharge that it is desirable to control: the intensity and the excitation. The *intensity* is a measure of the brightness of the light from the source. Usually an intense light is used so that the time of exposure will be short. By passing the discharge through the narrow opening of a capillary tube, the intensity may be increased. It may be still further increased by observing the capillary tube end-on, since the discharge is partially transparent. The *excitation* of the atoms is a measure of the energy they have absorbed and hence of the wave-lengths they are capable of giving off. If they have a high excitation—have absorbed a large amount of energy—they are capable of producing short wave-lengths. For producing these short wave-lengths a condensed discharge is used. If the light under examination is in the ultraviolet region, a quartz tube is used since glass is no longer transparent to the shorter wave-lengths. Cylindrical or spiral electrodes are employed to avoid overheating of the tube. The tube must be thoroughly baked out to rid it of foreign gases, and the gas in use can be continuously purified by circulating it through a system designed to take out the most prominent impurities. The tube may be filled with inert gases, in which case the gas that is to be excited can be maintained at a low pressure without disrupting the discharge. At low pressure there is less broadening of the lines. Moreover, collisions of the second kind with the atoms of the inert gas aid in the excitation of the spectrum.

An electrodeless discharge takes place between pieces of metal wrapped around the outside of a discharge tube and connected to a source of high frequency alternating current; this arrangement has the advantage that no electrodes are inside the tube to introduce impurities into the discharge or absorb the gases. Another type of electrodeless discharge can be obtained with a cylindrical tube mounted in the solenoid of a high frequency oscillatory circuit. The ions and electrons in the tube are accelerated in a ring, by the field, sufficiently to cause excitation of the gas by collision. The excitation is strongest at the periphery of the ring, and weakest on the axis, so that the amount of excitation needed to produce

particular lines may be studied by observing different parts of the ring.

Another type of low pressure discharge tube is the Schuler tube which contains an inert gas at a pressure of a few millimeters of mercury. It is used to produce the spectra of metals as well as the spectra of the inert gases. The cathode of this tube is hollow, and it is in this hollow that the emission is most intense. The advantage of this source is that it gives sharp lines of the first spark spectrum—that is, of singly ionized atoms, or atoms which have lost a single electron—clear up to the ionization limit where the ion becomes doubly ionized. To produce a spectrum of a particular metal, for example, copper, the cathode is made of that metal. If this is not practicable a cup can be made at the end of the cathode to hold the metal so that the latter will be vaporized by the discharge. The spectrum of the metal is intensified by collisions of the second kind with the atoms of the inert gas. The energy which the inert gas gives up most easily by collision with the metal is equal in amount to that necessary to ionize the inert gas. Therefore, by using different gases, different amounts of energy can be given to the metal in question. These different energies intensify different groups of lines, each energy intensifying those lines that require this much energy to be excited. In this way, the energy required to produce a given group of lines may be found, as the known ionization energy of a certain inert gas will intensify a particular group of lines.

In order to have as intense a source as possible, the voltage and current of the discharge tube must be large. But under these conditions the discharge becomes unstable and tends to form an arc in the tube. A way to prevent this is to operate the tube from a constant-current circuit similar to the one that has been developed for the transmission of power by direct current. A constant-current circuit will supply the same current to the Schuler tube under varying conditions of operation. There is therefore no danger of an arc, with a sudden rush of current, forming in the tube; for, if such a tendency did develop, the constant-current circuit would automatically reduce the difference of potential applied to the tube, thus maintaining the current at its original value.

Commercially this circuit is used to transmit power from Mechanicville to Schenectady. The alternators in Mechanicville are connected to the constant-current circuit so that an alternating current of 25 cycles/sec is available which will not change when the impedance of the circuit changes. This is then rectified by means of phanotron tubes and transmitted as a constant direct current to Schenectady. Here it is reconverted to constant potential, 60-cycles/sec alternating current in a thyratron circuit. It is interesting to see how this engineering development has been applied in spectroscopy.

(*2*) *The arc.*—An arc is obtained by passing a current from a constant source of potential through a pair of electrodes in series with a ballast resistance. When the electrodes are touched and drawn slightly apart, the current continues, being maintained by the material of the electrodes which gradually vaporize. As the current increases, the difference of potential across the arc falls, so that the series resistance is necessary to prevent excessive current and produce stable operation. The highest temperature in the arc is generally at the anode, where the material is vaporizing. If the slit, focused on the photographic plate, is illuminated by the light of the entire arc, different parts of the arc give different types of lines. The fact that spectral lines are always obtained, instead of circles or other geometrical forms, arises from the necessity of focusing the line of the slit on the plate to prevent the different wave-lengths from overlapping. The lines obtained from the neighborhood of each electrode of the arc are called *polar* lines, the "pole" being simply the electrode. These lines are due to transitions of electrons between the higher and intermediate energy levels in the singly ionized atom. The rest of the arc produces singly ionized lines of lower excitation, and also the lines arising from the normal atom with its full complement of electrons. This latter is generally referred to as the *arc spectrum*.

(*3*) *The spark.*—An electric spark is a high potential oscillatory discharge of some violence between fixed electrodes. A condenser and spark gap are put in series with a source of high potential so that it is really the discharge of this condenser that excites the spectrum. The spark gives some of the lines found in an arc together with lines of higher excitation. There are certain differences in the character of the arc and spark lines which make each useful for studying particular

groups of lines. The arc lines of low excitation show self-reversal; that is, the light emitted by the gas is absorbed in passing out through the surrounding cooler gas. This is also found occasionally for lines of low excitation in the first spark spectrum. The lines of this spectrum arising from transitions to the normal or lowest state, are more intense than in the arc. The spark gives polar lines at both electrodes. These are sharp, because of transitions to the low states of the more highly ionized atom, and intense but diffuse, due to intermediate and high transitions in singly ionized atoms. Some investigators find the negative pole of the arc a better source of the first spark spectrum than the spark itself. For the spectra of atoms that have lost more than two electrons—that is, the third spark spectrum and beyond—the spark is run in a vacuum. In this way the spectrum of copper atoms with 18 electrons removed has been obtained. Some of the lines of high excitation of the first spark spectrum are displaced from their normal wave-length and broadened, due to the effect on the atoms of the electric field of the spark; this action of the electric field is known as the *Stark effect.*

(*4*) *King's furnace.*—King's furnace consists of a hollow carbon tube within which the substance to be studied is vaporized in an atmosphere of hydrogen. The heat is produced by a current in the carbon tube itself. The temperatures, which may exceed 3000°C, can be accurately controlled, and can be measured with a pyrometer. The lines are sharp as there is no Stark-effect broadening. As the temperature is increased, first the arc lines of low excitation appear, then the more highly excited arc lines and the spark lines of low excitation. Thus an idea of the energy necessary to excite any particular line may be found from the furnace temperature needed to produce it.

Dispersion and photography

Next we turn to the second part of the general experimental procedure; namely, dispersing and photographing the radiation emitted by the source. The light source is first focused on a slit and the light is then dispersed either with a prism or a grating.

(*1*) *The prism.*—In a prism spectrograph, the radiation from the slit passes through a collimator, which renders it parallel, then through the prism, after which it is focused on the photographic plate. A prism disperses blue light more than red, and hence is used chiefly for the blue and ultraviolet end of the spectrum. Glass transmits down to about 3600A. Then quartz is used down to 1850A. Between 2000 and 1850A, the apparatus may be enclosed in an atmosphere of nitrogen to cut out the absorption bands of atmospheric oxygen. Below 1850A, a fluorite prism and lenses are used, and they are mounted in a vacuum to avoid atmospheric absorption. At 2000A the amount of dispersion produced by a prism is similar to that of a grating, but below 2000A the lines become fuzzy due to lack of resolving power of the prism. Fig. 1 illustrates the relative amount of dispersion of a prism and a grating for a small group of lines, known as a multiplet, from the arc spectrum of iron. The wave-length is about 4900A. It may be seen that the dispersion increases rapidly in the higher orders of the grating.

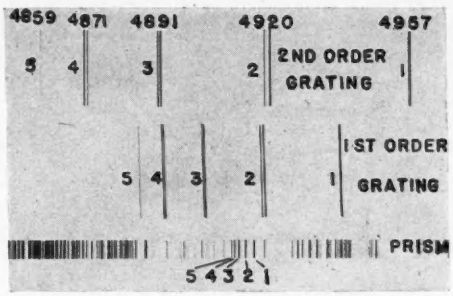

FIG. 1. Relative dispersion of prism and grating as shown by the principal lines of the $^7F-^7D$ multiplet of iron, FeI. (Courtesy of A. G. Shenstone.)

As quartz rotates the plane of polarization of the light passing through it, a prism for a quartz spectrograph may be corrected for this rotation by making it of two equal pieces cemented together in such a way that the first piece rotates the plane of polarization in one direction and the second piece, an equal amount in the opposite direction. Since large quartz prisms of this type are expensive, a Littrow mounting (Fig. 2) is often used. Here only the first half of the usual prism is employed, and the back surface is mirrored to reflect the light in the reverse direction after it has entered in the usual way. The light thus passes through the same piece of

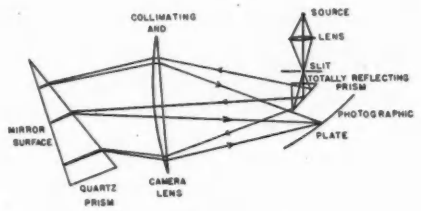

FIG. 2. Littrow mounting for a prism spectrograph.

quartz in opposite directions and there is no resultant rotation of the plane of polarization. The prism has the same amount of dispersion as the usual type of twice the size. Space is conserved by using the same lens as a collimator and camera; hence this type of spectrograph is less expensive than a conventional one. The plate may be slightly curved and placed at an angle with the beam. The system has to be focused for each region of wave-lengths to be photographed, and the apparatus maintained at constant temperature. There are two images of the source that are troublesome: a real image formed by the back surface of the lens acting as a concave mirror, and a virtual image formed by the front surface of the same lens also acting as a mirror. These are shut out as much as possible by suitable screens. The chief advantage of any prism is the greater intensity of the spectrum which it produces, thus allowing a much shorter time of exposure than with a grating. A prism is particularly useful for a preliminary survey of the spectrum, as in a low dispersion instrument the whole field appears on one plate. The great advantage of a grating, on the other hand, is its large resolving power which enables it to separate lines whose wave-lengths are only a fraction of 1A apart. The grating also gives greater dispersion than the prism for most wave-lengths; and the lines are easier to reduce to wave-lengths by comparison with standard wave-lengths since the dispersion is more nearly linear. It has recently been found possible to rule a grating with the grooves so shaped that most of the energy is concentrated in the first order on one side only of the central image. This should greatly lessen the time of exposure.

(*2*) *The grating.*—For photographing the ultraviolet region below 1850A, a grating in a vacuum is frequently used. This grating is ruled on glass,

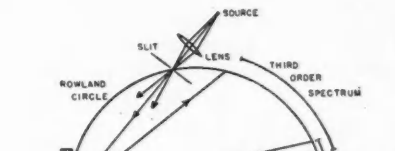

FIG. 3. Paschen mounting for a grating spectrograph.

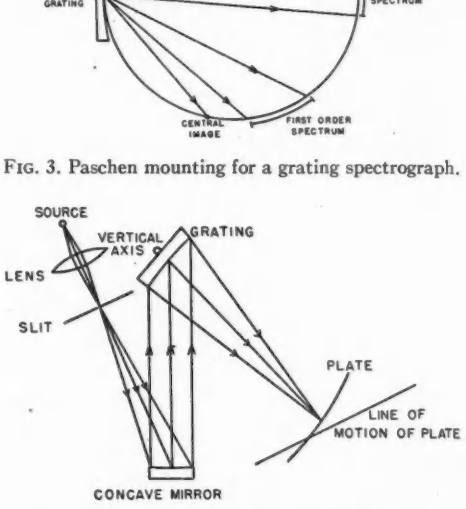

FIG. 4. Stigmatic grating mounting after Wadsworth.

and is a reflection grating of the concave-mirror type, so that the radiation from the slit is brought to a focus on the photographic plate without the use of any lenses which would absorb the lines sought. For short wave-lengths the grating is used at grazing incidence, thereby increasing the dispersion.

Gratings for use in the visible region of the spectrum are also concave mirrors but are ruled on aluminum deposited on a glass surface. Aluminum is especially useful from 3000 to 4000A since silver has a minimum reflecting power in this region. Some mountings are stigmatic and some are not. A stigmatic mounting gives a point image of a point source whereas an astigmatic mounting spreads a point source out into a line. The latter is a disadvantage because the intensity of the image is decreased, and images of the different parts of the source cannot be separated on the plate. Perhaps the most commonly used mounting is that of Paschen, shown in Fig. 3. The grating is set up tangentially to a circle of

diameter equal to the radius of curvature of the grating. In this arrangement, with the slit on the circumference of the circle, the grating gives a central image of the slit that is also on the circumference of the circle. The diffracted images appear around the circle, and the position of any particular order depends on the angle of incidence and the number of lines per unit length on the grating. The circle is frequently made 21 ft in diameter and photographic plates are mounted around the circumference. The plates near the normal are most advantageously placed, as at this position the dispersion is most nearly linear and the astigmatism is least. The Paschen mounting has the advantage that nothing has to be moved to photograph different parts of the spectrum. The lines may also be simultaneously photographed in several orders.

Gratings are subject to ruling errors which produce spurious lines or "ghosts" of the strong lines of the spectrum. There are three types of ghosts: Lyman ghosts, which are so far from the lines that the ghost of a red line might be in the green; Rowland ghosts, which are symmetrical on each side of the line near it, and are produced by periodic ruling errors; and nonsymmetrical ghosts between the symmetrical ones and the line. It is not so difficult to recognize these ghosts, but they mask faint lines in the spectrum that happen to fall at the same place on the plate. The stigmatic mounting shown in Fig. 4, although not extensively used, is of interest because it eliminates this particular difficulty of astigmatism; the arm carrying the plate rotates about the grating in a horizontal arc, and the plate slides in and out along the arm so that the spectrum may be focused.

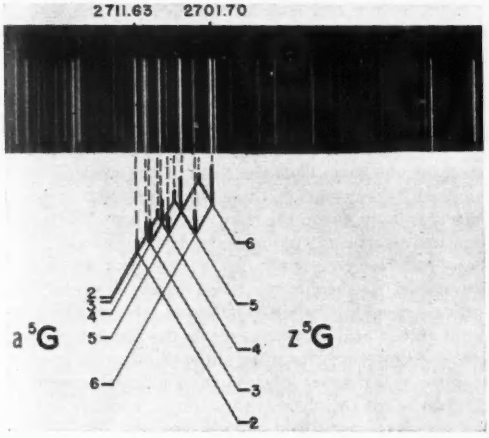

FIG. 5(a). a^5G-z^5G multiplet in Mn II. The standard iron spectrum is above the manganese. The lower term is on the left and the upper on the right. The lower term is inverted, i.e., the lower J values are higher. The slant lines from the initial and final levels intersect on the line corresponding to a transition between them. Equal differences occur where a pair of lines from the initial state intersects a pair from the final to form a small diamond-shaped parallelogram. The lengths of the vertical lines at the intersections indicate the intensities of the corresponding spectrum lines.

Wave number determination

After the lines have been photographed, it is necessary to find their wave-lengths. On each plate there has been photographed, not only the unknown spectrum, but a "standard" spectrum, usually of iron or copper, whose wave-lengths are accurately known. This procedure is illustrated in Fig. 5(a) or 5(b) where the upper spectrum is the iron arc standard and the lower one the spectrum due to a manganese arc. Enough standard lines are known so that they appear on the plate with few intervals between them of more than 10A.

Two standard lines about 200A apart are chosen and the distances from one of them to the unknown and standard lines in the interval measured; the plate is then turned around and the distances of the same lines measured from the other line bounding the interval, to compensate for errors in the first measurement. This gives the positions of the lines in this interval in milli-

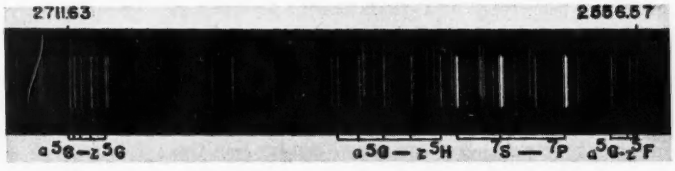

FIG. 5(b). To the left is shown the a^5G-z^5G multiplet of Fig. 5(a). In addition there are two other multiplets with the same lower term. The $^7S-^7P$ multiplet indicated contains the 3 strongest lines in the Mn II spectrum, ^7S being the normal state. There are 5 classified multiplets in the figure in addition to the ones marked. I am indebted to Dr. C. W. Curtis for the photographs and analyses of Mn II.

meters, starting from one standard line. Next, since the dispersion of a grating is approximately linear, it is assumed to be exactly so; and the wave-lengths of all the lines, both standard and unknown, are calculated by comparing their distances from one end-standard to the distance between the two end-standards. These calculated values of the standard wave-lengths are then subtracted from the known values and the differences plotted as errors. From this error curve, the correction to be added to the calculated linear value of any unknown line may be found. The procedure for a prism plate is similar except that one calculates the wave numbers of the lines between the two end-standards rather than the wave-lengths because the dispersion of a prism is more nearly linear in wave numbers. It is necessary, however, to use a theoretical dispersion formula to calculate the wave numbers as the dispersion of a prism is not sufficiently linear. In the far ultraviolet, where standards are rare, impurities in the source may be utilized to provide the standard spectrum. Hydrogen is a good impurity to use as it is usually present whether wanted or not. The hydrogen lines are easily recognized since the Doppler broadening is greater for the light hydrogen atoms. In the Doppler effect, if the emitting atom is receding from the slit, the wave-length is increased and vice versa; this spreads the line out symmetrically around its original position, the amount of the broadening depending on the velocity with which the emitting atom is traveling. If the atoms of different elements have the same average kinetic energy at the same absolute temperature, the light hydrogen atoms will move most rapidly and hence give broader lines than the other elements. Vacuum wave numbers are found from the air wave-lengths by Kayser's table, which gives the reciprocal and corrects for the index of refraction of the air at the same time.

Energy levels

Having a list of the wave numbers of the lines in the spectrum, we are now ready for the analysis that will yield the energy levels. The basis of spectral analysis is the Ritz combination principle, which states that, with certain limitations, the difference between the wave numbers of any two energy levels of an atom gives the wave number of a line emitted or absorbed by the atom. The wave numbers of the lines on the photographic plates thus represent differences between certain energy levels, and the object of the analysis is to find the wave numbers of these energy levels.

We will digress at this point into atomic structure to point out something of the origin and nomenclature of atomic energy levels. The simplest atom is hydrogen which, according to Rutherford's view, consists of a single positive charge and a single electron. On the earliest Bohr theory, this electron revolved in a circular orbit about the positive charge as a nucleus. Bohr assumed further that only those orbits or "stationary" states of the electron were allowed for which the angular momentum was an integral multiple of $h/2\pi$, where h is the Planck constant of action. The integer n giving the number of times $h/2\pi$ is contained in the angular momentum is called a *quantum number*, and a series of energy levels is obtained by letting n take on successive values. The electron does not emit or absorb energy as long as it is in one of these stationary states, but only when it makes a transition from one state to another. The energy emitted or absorbed is then equal to the difference in energy of the two states between which the electron makes the transition.

Next, Sommerfeld introduced elliptical orbits with the nucleus at the focus of the ellipse. There were now two momentums to be quantized, one corresponding to the angular motion of the circular Bohr orbits and the other, to motion along the radius vector joining the nucleus and the electron. The original Bohr quantum number, on which the energy depends, is now the sum of the two momentum quantum numbers. Thus the state of the electron is determined by any two of these three quantum numbers, since if two are given, the third may be found. The total quantum number n determines the semi-major axis of the ellipse and hence gives the distance of the electron from the nucleus. As the electron has a negative charge, n determines roughly the distribution of charge along the radius vector. Still another quantum number is introduced by the orientation of the plane of the elliptic orbit in space. In order to fix some direction in space with respect to which to orient the ellipses, the atom is assumed to be in an external magnetic field of fixed direction. The plane of the orbit is represented by the orbital angular momentum vector drawn perpendicular to it, and the component of this vector along the magnetic field determines the orientation of the orbit. The values of the possible components are again assumed to be integral multiples of $h/2\pi$. The external magnetic field is now allowed to vanish, leaving the atom with its orbits oriented in space in this rather artificial way.

Finally, in order to account for the structure of spectra, it is necessary to assume that the electron spins on its axis with a constant spin angular momentum having a quantum number $s=\frac{1}{2}$. For the components of spin angular momentum along the magnetic field to have differences that are integral multiples of $h/2\pi$, the spin must be either

parallel or antiparallel to the magnetic field. Thus its component $m_s h/2\pi$ along the magnetic field is either $\frac{1}{2}h/2\pi$ or $-\frac{1}{2}h/2\pi$, where m_s is the quantum number of the component of the spin angular momentum along the magnetic field.

To summarize, we distinguish the states of a single electron by the following quantum numbers:

n, the total quantum number,
l, the orbital angular momentum quantum number,
s, the spin angular momentum quantum number,
j, the total angular momentum quantum number,
m_l, the quantum number of the component of the orbital angular momentum along the magnetic field,
m_s, the quantum number of the component of the spin angular momentum along the magnetic field,
m, the quantum number of the component of the total angular momentum along the magnetic field.

These quantum numbers satisfy the following relations: $j=l+s$, a vector addition which yields $l\pm\frac{1}{2}$; and $m=m_l+m_s$, a scalar addition. In view of these relations it is necessary to specify only four quantum numbers to determine the state of the electron. The four usually chosen are either n, l, m_l, m_s or n, l, j, m. The orbital angular momentum quantum number l has the values 0, 1, 2, 3, $\cdots$, with $n=l+1$ for the state of lowest energy and n then increasing by one for each state of higher energy. The values of l are denoted by s, p, d, f, g, $\cdots$ so that when we speak of a d-electron, we mean one for which $l=2$. In the current state of the theory, the three quantum numbers n, l and m arise more naturally as integers in the solution of Schrödinger's equation so that the artificial way in which they have been introduced here is no longer necessary.

The situation grows more complicated if there is more than one electron in the atom. The electrons group themselves in shells around the nucleus, but it is only the valence electrons outside these closed shells that are of particular interest in giving the separations of the energy levels. A *configuration* of electrons is given by specifying the values of n and l for each electron in the atom. Here again it is customary to give just the n and l values for the electrons outside closed shells.

As in the case of a single electron, to find the energy it is necessary to know the total angular momentum, which is made up of the separate angular momentums of the several electrons in the atom. There are two common methods of doing this. It will be simpler if we represent the angular momentums by their quantum numbers. To obtain what is known as Russell-Saunders coupling, we add the orbital angular momentums of the separate electrons to give the total orbital angular momentum L of the atom, and the spin angular momentums of the separate electrons to give the total spin angular momentum S of the atom. Then we add L and S to get $J=L+S$, the total angular momentum of the atom. As we have seen that all the angular momentums are vectors, they must be added by vector addition. Also, the numbers obtained for any sum must differ by an integer so that the number of values for the sum of two vectors is strictly limited. Adding L and S, for instance, gives all values of J which differ by an integer between $L+S$ and $|L-S|$. If $L \gtrless S$ there will be $2S+1$ such values of J; hence $2S+1$ is known as the *multiplicty*. The values of L are denoted by the letters S, P, D, F, G, H, $\cdots$. The group of energy levels with given values of L and S and different values of J form what is known as a *term*, each level of which is designated by writing the multiplicity as a superscript on the left of L, and the total angular momentum as a subscript on the right; thus ${}^{2S+1}L_J$ or, specifically, ${}^3D_2$ for $S=1$, $L=2$, and $J=3$. All the lines arising from the transition of an electron from the energy levels of one term to those of another are known as a *multiplet*. It is observed empirically that those transitions are most likely to occur for which the selection rules $\Delta S=0$, $\Delta L=0$, ±1, and $\Delta J=0$, ±1 hold, where ΔS, ΔL and ΔJ are the changes in the corresponding quantum numbers in going from one level to the other. In addition, the transition from an upper level with $J=0$ to a lower one with $J=0$ is forbidden. The relative intensities of the lines given by these transitions are found to have definite values. Those lines for which J and L both increase or decrease are the most intense, and of these the intensity increases as the value of J increases.

The second method of combining the angular momentums of the separate electrons to get the total angular momentum of the atom gives jj coupling. Here we add the spin and orbital angular momentums of each electron to get the total angular momentum of the electron. The total angular momentums of the separate electrons are then added to give the total angular momentum of the atom. Here the energy levels do not form terms, but each level is characterized by its value of the total angular momentum J and the separate j values for each electron. If neither of these two methods gives energy levels corresponding to those observed, the two methods must be combined in what is known as *intermediate* coupling. The final states of the atom are given simply by the value of the total angular momentum J.

We now return to the analysis of the wave numbers of the lines of the spectrum to obtain the wave numbers of the energy levels. The first step is to mark all the wave numbers in the list that represent lines for which the energy levels have been found in a previous investigation. It often happens that a few of the most prominent terms in a spectrum have been known for several years. Visual estimates of the intensities of the lines from the darkening of the plate are useful in identifying lines, as the wave-lengths do not always agree exactly with those observed by the previous investigator. Since the relative intensities of a group of lines forming a multiplet are known, as has previously been mentioned, the intensity will aid in telling whether or not a line belongs to a particular multiplet.

After the wave numbers of the known lines have been deleted from the original list, the next

step is to look for pairs of wave numbers with equal differences. If the wave numbers of the levels of the term of lowest energy, and hence the wave numbers of the separations of its levels, are known for the spectrum, the wave number of the separation between the levels of lowest energy of this term is subtracted from each wave number in the list to see whether it gives another wave number in the list. If it does so, the two lines belonging to this pair of wave numbers may be considered to arise from the same upper level, which is thereby located with respect to the term of lowest energy. By subtracting the wave number of the separation between the levels of lowest energy from all the wave numbers in the list, a set of pairs of lines with equal wave number differences is obtained. Then the wave number of the separation between the levels of next higher energy is subtracted from all the wave numbers in the list to get another set of pairs of lines. If one of these pairs contains the line of smaller wave number in a pair of lines obtained by using the separation between the levels of lowest energy, then there is a group of three lines coming from the same upper level to the term of lowest energy. This subtraction is carried out for the wave numbers of all the separations of the term of lowest energy.

This can now be done automatically, by a machine that gives all pairs of lines with the same wave number difference. Holes spaced according to wave numbers are punched in a paper tape and then a photograph is taken of the light transmitted by the tape as it runs in a loop over two sprockets (*A* and *B*, Fig. 6). If a hole in the upper tape coincides with a hole in the lower tape at the arrow *C*, a spot appears on the photographic paper *D* below the tape. The photographic paper moves at right angles to the direction of the motion of the tape so that, as successive holes coincide under *C*, a line of dots is produced on the photograph. Each of these dots corresponds to an identical length of tape in the loop on the right and hence to an equal wave number difference between the two lines.

The next step is to try to group the sets of lines from common upper levels into multiplets and thus group the levels into terms. To do this, the pairs of lines which were found to have a wave number difference equal to that of the wave number separation of a pair of levels of the term of lowest energy, are listed in a square array. An observed multiplet which actually has been listed in this way is shown in Table I. Across the top

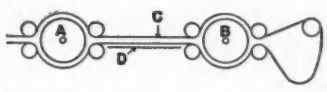

FIG. 6. Mechanical interval sorter (G. R. Harrison).

are given the J values and wave numbers of the levels of the term of lowest energy with their proper designation in terms of their quantum numbers. Between each pair of wave numbers, the wave number of their separation is written in italics. Next, below each pair of wave numbers are written the wave numbers of all the pairs of lines that have the same difference in wave number together with these differences. On the left, the J value and wave number of the upper level of the lines in each row are given. The wave number of the upper level is obtained by adding the wave numbers of the lines to the wave number of the level of the term of lowest energy at the top of each column. Again the differences between the wave numbers of the levels of the term of higher energy and the corresponding ones between the wave numbers of the lines are written in italics in a horizontal row between each pair of wave numbers. As a further aid in identifying the lines, the visual intensity of the line is given in parentheses above its wave number. A search is then made for multiplets. This is aided by the selection rules previously mentioned, which give the allowed transitions between the different levels. It may be seen that these selection rules actually do describe the lines listed in Table I, and also that all the lines predicted by these rules appear. If the separations between the different levels of a term which is being sought by means of the square array in Table I are known, then, when some levels have been found, the positions of the others may be predicted. This makes it easier to pick out the proper pairs of lines to go in this particular array. These separations are given by the *Landé interval rule*, which states that they are proportional to the larger J values of the two levels. Thus the intervals of $^5G_{6,\,5,\,4,\,3,\,2}$ are given by the proportion $^5G_6$-$^5G_5 : {}^5G_5 - {}^5G_4 : {}^5G_4 - {}^5G_3 : {}^5G_3 - {}^5G_2 = 6 : 5 : 4 : 3$. Each separation divided by the larger J value should give the same number. If this is carried out for the term of higher energy z^5G of Table I, the result is $31.15/6 = 5.19$, $24.74/5 = 4.95$, $20.70/4 = 5.17$, $16.80/3 = 5.60$. These numbers are

seen to be roughly equal. The rule does not hold for the term of lower energy, a^5G, however; this indicates that Russell-Saunders coupling, on which the rule is based, does not hold for this term.

When a group of lines obeying the selection rules with the proper intensities is found, it gives the quantum numbers and energy levels of a term of higher energy. The multiplet of Table I can be recognized as such from this method of tabulation. It happens that this is a multiplet from Mn II, the first spark spectrum of manganese, which is of interest since it was in this spectrum and the arc spectrum of manganese that Catalan first found, in 1922, multiplets that were more complicated than could be attributed to triplet-triplet combinations. Since the lower term is a ^5G and $\Delta S=0$, the upper term is a quintet. Again the J values of the upper term must be 6, 5, 4, 3, and 2, to account for the transitions found; hence $L=4$ and the upper term is also ^5G. The diagonal character of the pattern and regularity of the intensities are easily recognized in the example we have given. In the process of analysis, the array of Table I would contain many more pairs of lines, with equal differences, than those shown. Some of these differences would be fortuitous, due to a lack of accuracy in the wave numbers, and others would belong to combinations of the levels of lower energy at the top of the table with other terms. If the line differences are inaccurate, and the intervals and intensities somewhat irregular, the multiplet does not stand out as in Table I so that it is difficult to tell which lines belong to it.

TABLE I. Mn II $3d^5\ 4s\ a^5G-3d^5\ 4p\ z^5G$ *multiplet. Energy levels, spectrum lines, and differences are given in wave numbers. Estimated intensities appear in parentheses above each line. Differences are in italics.*

$3d^5\ 4p\ z^5G$	J Values	$3d^5\ 4s\ a^5G$ 6	5	4	3	2
		LEVELS 27546.90 *24.05* 27570.95 *12.35* 27583.30 *4.93* 27588.23 *0.80* 27589.03				
		(30)	(1)			
	6	64549.72	37002.83 *24.08* 36978.75			
		31.15	*31.15*	*31.15*		
		(7)	(25)	(4)		
	5	64518.57	36971.68 *24.07* 36974.61 *12.35* 36935.26			
		24.74	*24.73*	*24.74*		
			(10)	(20)	(4)	
	4	64493.83	36922.88 *12.36* 36910.52 *4.91* 36905.61			
		20.70		*20.70*	*20.78*	
				(8)	(8)	(2)
	3	64473.13		36889.82 *4.93* 36884.89 *0.78* 36884.11		
		16.80			*16.77*	*16.83*
					(6)	(8)
	2	64456.33			36868.12 *0.84* 36867.28	

Once the lines with differences equal to the separations of the term of lowest energy have been grouped in as many multiplets as possible, the process is repeated for other terms, including the new ones as they are found. The accuracy of the analysis is strengthened if the same term, found combining with one term of low energy, is found combining with another term of either lower or higher energy. If a multiplet fits into several such combination schemes, its levels become well established. Thus gradually the terms of higher energy are located until finally the spectrum is analyzed.

Since the most difficult part of the foregoing analysis is to recognize multiplets, many additional aids have been developed for this purpose. First, there are *series formulas*. A series of levels given by such a formula arises when the total quantum number of a single electron starts with $l+1$ for the lowest level, as we have seen previously, and increases by unity for each higher level. Several types of formulas have been developed empirically from which, if the first few levels of a series are known, levels of higher energy can be calculated. In the second place, much information may be gained about a spectrum by comparing it with the spectra of neighboring atoms, with the same number of electrons, in the periodic table. Such atoms produce spectra so similar that the terms of one may be predicted from those of the others. A definite rule known as the *irregular doublet law* connects the spectra of neighboring atoms; it states that in any transition in which the total quantum numbers of the electrons do not change, the rate at which the frequency increases with increase of atomic number is constant. Finally, the *Zeeman effect*—the splitting of levels when the source is in a magnetic field—also aids in assigning terms, since the Zeeman pattern of a line in Russell-Saunders coupling is alone sufficient to give the levels that produced the line. These aids to analysis are especially helpful when no terms in a spectrum are known in advance. Then, by one of these methods, a likely interval must be inferred and tried out to see whether it will account for some of the strongest lines. Once a term is established, the analysis can proceed as previously described.

The lines of the multiplet which has been analyzed in Table I are shown in Fig. 5. The

constant differences between pairs of lines may be worked out from this figure. The levels of the upper and lower terms are given on each side, and lines are drawn from each level so as to intersect under the line represented by this transition.

The theory of spectra[1]

We now proceed to see how the atomic energy levels which have been found from the wave numbers of the lines on the photographic plate may be calculated theoretically. The theory of spectra has arisen from the discovery of certain empirical rules by which the observed energy levels of a spectrum could be interpreted. Thus it was first found that the levels could be arranged in series. This has been continued until now series formulas of the Ritz type have been developed to account for parts of the most complex spectra. The levels of higher energy of different series overlap so that they perturb each other, making it difficult to follow the series to the limit; namely, to where ionization takes place. These series arise when the total quantum number of a single electron increases in integral steps as the excitation increases. There is a separate series for each level of the configuration of which the electron is a member.

The levels of these series were interpreted by Bohr as the stationary states in which the atom could remain without losing any of its energy. The Ritz combination principle is then interpreted as saying that the atom emits or absorbs light by changing from one of these energy states to another. Moreover, since the frequency of the light emitted is given by the famous relation

$$h\nu = E_1 - E_2, \qquad (1)$$

where h is the Planck constant, ν the frequency of the light, E_1 the initial energy of the atom, and E_2 the final energy, Bohr's interpretation says that E_1 and E_2 represent the energies of the different levels in the series. The Bohr theory made use of classical mechanics, with the addition of certain quantum conditions, and was able to account for a large amount of spectroscopic material. There were, however, several things for which the theory was inadequate. It was incomplete in describing the interaction of an atom with an electromagnetic field, gave no relative or absolute intensities of the lines, and was unsatisfactory in predicting the energy levels of atoms containing more than one electron. The theory was nevertheless a great stimulus to experimental analysis which in turn produced a wealth of material that could be used to develop the next step of the theory, quantum mechanics.

To calculate the stationary states of energy by quantum mechanics, Schrödinger's wave equation is used. In this equation the original model of Rutherford and Bohr loses some of its pictorial quality, but the theory may still be pictured in terms of energy level diagrams. The first step in the calculation is to find an expression for the total energy of all the electrons in an atom and then to find, by solving the Schrödinger equation with proper boundary conditions, which values of this energy are allowed. It turns out that the equation restricts the allowable energy to certain discrete values. Not only does the equation lead to these values of the energy, but it also determines a certain function representing each electron and known as a *wave function*. The integral of the square of the absolute value of this function over a certain volume is interpreted as the probability of finding the electron in that volume. This means that the integral of the function over all space is unity, since the electron must be somewhere in space. When this probability integral is multiplied by the charge on an electron, it gives the charge to be found in the volume over which the integral is extended.

The expression for the energy of the electrons, which is to be used in Schrödinger's equation to find the allowable values of this energy, is made up of the sum of their kinetic and potential energies. The potential energy of each electron depends on the presence of the nucleus and the other electrons as well as on the state of the electron itself. The type of function used in the potential energy to express this dependence determines the wave functions and the arrangement of the resulting energy levels, and also leads to difficulties in solving the equation. The first part of the expression for the potential energy of an electron in an atom is a term $-Ze^2/r$; this is the potential energy due to the Coulomb attraction of the nucleus for the electron, r being the distance of the electron from the nucleus. If this

[1] For a full account see E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra* (Cambridge Univ. Press, 1935).

potential energy $-Ze^2/r$ is used alone, the equation breaks up into the sum of equations for single electrons; and so gives a series of levels for which the energies are the sum of single electron energies like the ones found in hydrogen. There is no structure to these levels; all the different states of the atom associated with the same total quantum numbers of the electrons have the same energy. The states in this case are said to be *degenerate.*

The next part of the expression for the potential energy to be used, to get more accurate values for the energy levels, is the Coulomb repulsions between all the pairs of electrons. Each pair of electrons is found to give a potential energy of amount e^2/r, where r is now the distance between the pair of electrons. This is known as the electrostatic interaction of the electrons and gives the terms in Russell-Saunders coupling. The original level for a particular configuration of electrons with definite values of n and l is now split, due to the electrostatic interaction of the electrons, into several levels which are characterized by definite values of the total, L, and spin, S, angular momentum quantum numbers of the atom. Since it has not been possible to solve Schrödinger's equation directly when the electrostatic interaction of the electrons is included in the potential energy, a method of successive approximations, known as the *method of the self-consistent field*, was devised by Hartree.

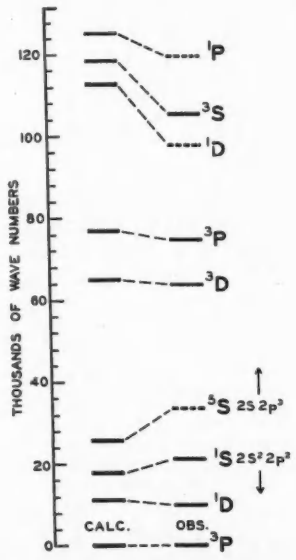

FIG. 7. Term values of C I. The observed values which are dotted lines are estimates: ^5S from the irregular doublet law, and ^1D and ^1P from the irregular doublet law and comparison with the isoelectronic sequence N II and O III. No combinations are observed for these levels. (Observed values by B. Edlén.)

We turn now to consider Hartree's method. Each electron moves in the field of the nucleus and of the other electrons. The field of the electrons depends on their charge distribution which, as has been seen, depends on the wave functions. We are thus in the position of trying to solve an equation for an unknown when some of the terms of the original equation depend on the answer we are seeking. This difficulty is circumvented by estimating the contribution of each electron to the field in which the other electrons find themselves. With this field known, the equations may now be separated and solved for the wave function of each electron. These wave functions are then used in turn to calculate the contribution of each electron to the field. The result should agree in each case with the original estimate. If it does not agree, the estimate is altered slightly and the calculation repeated until it does. Then, after the proper field has been found, the energies may be calculated from the wave functions by a method developed by Slater. The results of a complete calculation of this sort, from Hartree wave functions for carbon, are shown in Fig. 7. There is considerable discrepancy between the calculated and observed values, due mostly to the fact that only one electron configuration at a time has been considered in solving the Schrödinger equation. This complete theoretical treatment of the atom by Hartree's method involves extended numerical work which becomes increasingly difficult as the atoms become more complex, with increasing numbers of electrons.

If the field in which the electrons move has not been calculated, Slater's method still will give considerable information about the energy levels. The levels come out in this case expressed in terms of certain parameters which cannot be calculated without the field. Different parameters are obtained by using different potentials in the original Schrödinger equation so that, if only the electrostatic interaction is used, they give Russell-Saunders coupling. Since it is too

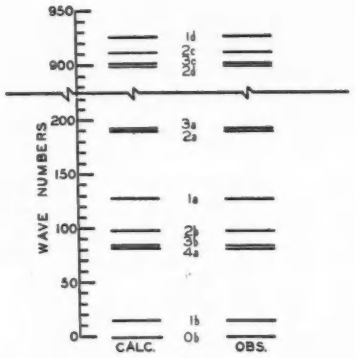

FIG. 8. Energy levels in Ne I $2p^5\,3d$. (Observed by F. Paschen; calculated by J. B. Sampson.)

much work to evaluate the parameters theoretically, they must be found from the experimental values of the energy levels by equating the calculated and observed energy values, and solving the simultaneous equations thus obtained. Now, in order to have the theory predict any terms, there must be more terms than there are parameters. Usually the parameters are calculated by the method of least squares from all the term values and then used to predict these same values. This avoids undue influence of the error of a single term on the parameters. It often happens that a particular term is much more in error than are the rest. If this term is one of a few used to calculate the parameters, they will not be accurate. On the other hand, if it is one of many terms used, the parameters will be more nearly correct.

The only potential energies which we have thus far considered are those due to the electrostatic forces in the atom. There are also electromagnetic forces which arise from the motion of the electron. This motion is of two types, the orbital motion about the nucleus and the spin of the electron on its axis. The orbital motion of the electron is equivalent to an electric current and gives rise to a magnetic field. The spin of the electron results in a magnetic moment; and thus the electron, because of its spin, is acted upon by the magnetic field of the orbital motion. The potential energy of this spin-orbit interaction of the several electrons together depends on the total orbital and spin angular momentums of the atom. If this potential energy of spin-orbit interaction alone is added to the nuclear electrostatic potential energy, ignoring the electrostatic interaction of the electrons, *jj* coupling is predicted. Thus in cases where the electrostatic interaction is small compared to the spin-orbit, *jj* coupling results; and conversely when the spin-orbit interaction is small compared to the electrostatic, Russell-Saunders coupling results. If, in Russell-Saunders coupling, the effect of the spin-orbit interaction is added as a small perturbation, each term will be split into a group of levels depending on the different values of J. The multiplicity, $2S+1$, is the maximum number of levels into which each term splits.

Finally, there is the case in which both the electrostatic and spin-orbit interaction are important, so that the potential energy of each must be used simultaneously in the Schrödinger equation. This gives intermediate coupling in which the levels are designated only by their values of the total angular momentum quantum number J of the atom. A calculation of this sort, evaluating the parameters from the experimental energy levels by least squares, in the case of the $2p^5\,3d$ configuration of neon, is shown in Fig. 8. It was the first complicated spectrum ever analyzed. The agreement between theory and experiment is excellent, as all the differences between observed and calculated values are less than one wave number. This indicates that the levels are not perturbed by interactions which have been neglected in the theory.

An interesting example of a complicated configuration in intermediate coupling for which the theory may be put in a simple form is $3d^95g$ in Cu II as shown in Table II. It was found that

TABLE II. *Energy levels of* Cu II $3d^95g$.*

J VALUE AND LEVEL DESIGNATION	OBS.	CALC.	ERROR
$6c$, $5d$	2094.43	2094.34	−0.09
$5c$, $4c$	2127.96	2128.31	0.35
$4d$, $3c$	2116.43	2116.40	−0.03
$3d$, $2d$	2082.65	2082.42	−0.23
$7a$, $6b$	17.67	17.57	−0.10
$6a$, $5a$	52.08	51.98	−0.10
$5b$, $4a$	55.99	56.14	0.15
$4b$, $3a$	42.77	42.53	−0.24
$3b$, $2a$	21.61	21.35	−0.26
$2b$, $1b$	0	0.55	0.55

* The observed values are from the analysis of A. G. Shenstone; the calculated values, from G. H. Shortley and B. Fried. I am grateful to Dr. Shortley for sending me these results before their publication.

each level had the characteristics of two different values of J, indicating that the levels fall together in pairs, which is an unusual occurrence. It was found from the theory that all the interaction parameters were negligible except the leading one of electrostatic interaction and the one giving the spin-orbit interaction of the core of the nine d-electrons. Therefore the structure of the 20 levels listed in the first column of Table II is given by two parameters. As may be seen, the levels in the table fall into two groups, separated, roughly, by 2070 wave numbers. This is the separation due to the spin-orbit interaction of the core. The structure of each group is given by a single parameter of electrostatic interaction. In a normal case, the splitting of the levels is due to all the parameters, so that the fact that some of them are negligible explains why the levels fall together in pairs as is observed. Not only is this doubling of the levels explained, but the numerical agreement is excellent also.

We have seen how spectra are obtained in the laboratory and analyzed into energy levels. A theory of atomic structure based on the Schrödinger equation has arisen in recent years, and we have seen that it is able to account for these energy levels, in some cases quite satisfactorily. It would be desirable to be able to predict theoretically, with sufficient accuracy to aid in the analysis, the energy levels of spectra that have been difficult to analyze. Although there have been a few successful attempts to aid in the analysis in this way, the theoretical methods of calculating energy levels in the more complicated spectra will have to be simplified and the results made more accurate than they now generally are, if the theory is to be of use to the experimenter.

Presentation of a Portrait of Professor G. W. Stewart to the Department of Physics, University of Iowa

ON June 19, a portrait of Professor George Walter Stewart was formally presented to the Department of Physics of the State University of Iowa by the fifty-two living Ph.D.'s in physics and the present members of the staff. The portrait was painted by William McCloy, of the art faculty of Drake University, and will be hung in the graduate reading room of the Mathematics-Physics library. The presentation was made at a dinner attended by thirteen of the Ph.D.'s, and a large number of visiting physicists and members of the University faculty. Dean-Emeritus Carl E. Seashore, of the University of Iowa, spoke at the dinner and Dean Homer L. Dodge, of the University of Oklahoma, gave the presentation address.

After calling attention to the importance of the individual faculty member in the development of a university and mentioning the names of Hinrichs, Nipher, Veblen, and Guthe as those associated with the early development of the department, Dean Dodge called attention to the fact that Professor Stewart's service at Iowa coincides almost exactly with the development there of advanced graduate study in physics. The first doctor's degree in physics was conferred on Paul Sieg, now President of the University of Washington, in 1910, one year after Professor Stewart came to Iowa; the second doctorate was conferred on Dean Dodge, in 1914. A part of Dean Dodge's remarks follow:

"First of all I recall Professor Stewart as a kindly man. He took an unusual personal interest in each student, helping him to realize his possibilities and revealing to many, possibilities of which they were themselves unaware. Mrs. Stewart always shared in this personal interest and there was always a place for graduate students in their hearts and home. One of his former students said to me recently, 'Stewart certainly takes care of his students and has an uncanny ability for finding them positions for which they are adapted.'

"With students, as with himself, he was exacting. He lived and taught devotion to the job, the burying of oneself in the objective. Some students were restive under this rigid spiritual discipline but all profited by it as students, and in after years. I use the word 'spiritual' advisedly, for I believe that we have all recognized that Professor Stewart is devoted to physics as if it were a god to be worshipped and to be served. His devotion and his service have been expressed in many ways. As administrative head of the department he has helped to make it one of the leading departments of the country. He has been devoted to his own research and through it achieved eminence as evidenced by his recent election to the National Academy of Sciences, but, more especially, by the inherent excellence of his many contributions. He has been interested in physics instruction, and has aided materially in its advancement through the organization of special service courses and through his writings. A leader in the American Physical Society, he has aided every effort to advance the science of physics nationally and, especially, in the Middle West."

After the portrait was unveiled, Professor Stewart responded with the paper on "The Human Values of Physics" that appears on page 312 of this issue.

The Human Values of Physics

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WHAT are the human values of physics? The words "science" and "invention" are often coupled just as if science, and more especially physics, represents chiefly an invention-producing effort of man. The brief discussion that follows will hold that science in general and physics in particular are important aspects of man's intellectual life, that science has a profound civilizing influence, and that this contribution will not remain static but on the contrary will grow to larger and larger proportions.

There are many things that affect what we commonly call civilization. It is quite impossible even to review them all, much less to make full comparisons. So these remarks are to be sharply limited to the human values of science and especially of physics without comparisons with any other aspects of knowledge.

In speaking of human values, one should have an awareness of a large measure of fallibility. Indeed there may be a great difference of opinion as to what is valuable and what is not. After all, man himself, who is a variable, must of necessity be the basis of measurement. In the beautiful, luxuriant, tropical island of Bali, where nature is so lavish and the struggle for sustenance is so simple, many of the Balinese live in compounds behind high walls within which some of the ground is hideously bare and ugly. They choose to do it. For with the high wall they shut out the evil one who can move only a certain height above the ground. Within this barricade their animals denude the soil of every growing thing. Thus some of these Balinese shut out the beauty of nature, where she gives so lavishly, and make their surroundings dismal, because their tradition teaches the need of protection from the evil one. This custom, though it may seem foolish to us, undoubtedly has a mental value, as indeed does every accepted tradition. Perhaps all we can ever endeavor to do is to estimate values carefully, though imperfectly, always being wary of the pseudo-authoritativeness of tradition. We should make every endeavor to be certain that we are not shutting out possibilities in life by a devotion to tradition. So while one does not wish to give opinions with entire confidence, yet opinions must be given if we are to have any discussion at all.

As prefatory to what follows, consider the value of government. Though the establishment of government by a people is a desirable development of civilization, yet its over-emphasis may prove to be quite the opposite. We look back to the fanaticism of religious wars, where creed was not the servant of man but his master. Creed was above all. Today, the lovely people of Japan, through the supremacy of government, even over man himself, have become guilty of nothing short of barbarism. In Germany, through a similar fanatical form of patriotism, the people have been led to indulge in gross inhumanities and injustices and have spread fear throughout not only Europe but the whole world. These are but representative examples of the very imperfect civilization of today of which we in the United States of America are a part. In the light of the brutalities and injustices of history, we may be said to be more highly civilized today. But when one looks at individual man, his love of beauty, of home, of simple happiness, of friends, his own desire for kindliness and generosity, can one think that our organized society today can possibly be man at his best? Surely, what we call civilization has not yet reached a high state. Society has a long evolutionary journey before it, and this can occur only if the component individuals actually change. Naturally, this will not be a biological development, but one of altered intellectual interest, attitude, and conviction. We may then inquire as to what science can do since there is so much to be done. What human values has science? It is quite fitting that the physicist should desire to consider the possible contributions of his science not only to the individual, but to civilization as well.

Science is so often regarded as a thing separate from man, in contrast to art, which is regarded as a form of man's expression. This is unfor-

tunate. Science is not impersonal. It is not neutral. It is truly man's product, man's self-expression, the result of man's thought. It is not absolute truth but a form of expression of man's logical consideration of his environment. Science has in it all of man's mental limitations. It may appear cold, unfeeling and ruthless in its conclusions, not because it is an agency external to man, but because man's efforts at thinking of matter produce just such a structure. In science are man's contemplations, reasonings and conclusions. In it also are his likes and dislikes, his prejudices, his inertia, his inflexibility. Science is a very human record. True, science contains a collection of facts, but in its effort to organize them and to set forth simplified and approximate "laws," science reflects man himself. This is its *living* quality. So it must be remembered that science is man's expression of thought, and he who would teach it must be forever conscious of this human quality. To omit this view would be to leave out the possible gain to the student of the appreciation of man's self-expression as such. That scientists should sometimes appear to be living in a mass of technicalities is not surprising. The same may be said of the artist. In both art and science, technicalities are essential. These are the necessary means by which man can give expression to his thought and effort.

What then are some of the influences of this expression of man's mind, called science? Undoubtedly the influence one thinks of immediately is that which accrues from an appreciative understanding of one's environment. This certainly augments one's satisfaction in the quality of life. But perhaps an even more fundamental contribution of science rests in the fact that it increases man's confidence in his own ability to think and thereby to arrive definitely somewhere. The inventions and practical applications of science have had a value far exceeding their intrinsic worth, for they have demonstrated concretely that man's thinking is not merely a fruitless exercise. He can by taking thought actually arrive, not at perfection, but at something definitely useful. In fact, while man cannot pick himself up by his own bootstraps, he can actually fly, which is much better. It is the gradual accumulation of this sort of confidence in man's ability to reason and to arrive that does and will lead to greater cooperation between men and even between nations, and to more rapid and stable attainment in any changing social order.

Coincident with this, is an increase in man's confidence in his own creativeness, and by this I refer specifically to man's everyday activity. Today is not just like yesterday. Each day brings a new combination of circumstances, a new environment, and in adjustment thereto one must do something that has a quality of newness, that is really creative. The works of the great masters in art may not inspire us to think that we also can create. But in science there is a difference. Here heights are attained by a step-by-step process, each of which is within the strength of most students; and this is more like the kind of problems one meets in life itself. We gain confidence that we can build something new on the past. It is just this gain in confidence that may aid in producing success. It is this that enables men to face depression not helplessly, but with courage. It is this that marks the difference between leadership and failure. I deem this aid of science in establishing more completely man's confidence in his creative powers to be of far-reaching importance.

In science we find an unusual opportunity to develop a critical mind, a mind wary of foggy thinking, of half-truths, and of fruitless consideration of unverifiable facts. Any habit that becomes a *conscious* one is of general value. Science cultivates a conscious habit of seeking those materials that make clear thinking possible. This habit increases the stability and poise of the educated man. Science will not destroy the anger of nations or of men, but the development of the critical mind will lessen it. The critical mind, if critical enough, if it goes deeply enough, leads to tolerance and permits loyalty without intolerance. Science will help.

Science is of philosophic importance, and this must be recognized in any statement of values.

Science ministers to man's physical needs; it attempts to free him from suffering and illness. It not only recognizes the value of man himself but is the good Samaritan. One may have a classification of human values in his mind, yet without effect upon his own conduct. The effort of science to minister to man's body as well as

to his mind is an evidence of the breadth of its human values.

And now, having mentioned briefly the influence of science upon the individual and indirectly upon civilization as a whole, I wish to refer more specifically to physics. Each science has its own special feature or its specialized attainment as well as those general ones of which mention has already been made. Thus one of the greatest scientific opportunities of chemistry may be said to be its manifold and constantly changing chemical products, and its increasing knowledge of the structure of molecules. In biology, a most important objective is an understanding of the functions of the living cell. In physics, the most fundamental task is a detailed understanding of matter, not only its so-called physical properties, but the nature of forces between atoms and within the nuclei of atoms themselves. And it is both gratifying and remarkable that the human mind, through the development of the marvelous science of mathematics, has arrived where its understanding far outruns its powers of visualization. This intellectual activity is in itself a matter of great epistemological interest. Here is the atom, indescribably small, far smaller than any possibility of microscopic detection, containing within its cloud of electrons another speck, the nucleus, about one millionth the diameter of an atom. It is this vanishingly small aggregate, the nucleus, that the physicist now sets up his equipment to study; and it is interesting to notice that this intellectually refined study requires huge apparatus weighing many tons. One may surmise that nuclear physics may become the most expensive, the most cooperative, and the most intensive intellectual onslaught in history. The physicist does not yet see what effect on man this great conquest will have; but he is confident, first, that such a highly intellectual endeavor will have a favorable effect upon man's attitude, and second, that since the investigation is fundamental, it will in time prove itself important to every science.

All of the foregoing reflects the mind of the physicist at work. It affects his faith in his own service. It inspires his teaching so that it far outreaches technicalities. It increases his self-respect, for his mission in life is a laudable one. But he is not deceived by any over-statement of the "human value of physics." Quantitatively, the influence of any individual, with but few exceptions, is very small indeed. But though small his service, the physicist rejoices that his effort is in a commendable direction, that his service is at least one of quality.

Then we can be certain that the influence of science upon the decisions of individuals and of nations is far greater than its actual content may seem to warrant. For as the balance of physical forces in the production of weather is relatively easily disturbed, so in important problems that man confronts, whether in his own life, in his social contacts, or in his organized governments, decisions finally reached are strongly influenced by mental attitudes, by man's confidence in his own mind. As an example in recent history, consider the possible result of a certain, quite definite lack of confidence on the part of Japan. She knew her economic problems were not understood by any other nation and concluded that other nations never would understand. This conviction made cooperation impossible for her. It had much to do with the taking of Manchukuo, as well as her boldness in defying the League of Nations, and her influence through success in this respect upon Mussolini and the Ethiopian conquest. Can anyone fail to see that any influence, even though slight, upon men's confidence in the power of mind and willingness to face facts may easily alter history? So I have described the quality of the human values of science and not their magnitudes.

I conclude by saying that we physicists, while rejoicing in the direct utility of our science, in the beneficence of engineering, in the aid to other sciences which contribute to man's health, comfort, and productiveness, should be clearly conscious of these other human values which have been here selected for emphasis. Teachers of physics can and should study how, without lessening the technics, the students can benefit by the living quality of physics and its undeniable possible influence upon the attitude and decisions of the mind.

Physics in the Liberal Arts College

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LIBERAL arts students of today approach the study of physics with a curious assortment of motives. The utilitarian motive, for example, is not entirely absent, though it does not dominate the scene as it does in technical schools. Still, the radio "fan," the budding engineer, and the premedical student all expect to receive a contribution which can be turned to practical account. There is always a certain proportion, as in other subjects, who have been attracted by personal contacts with fellow students or with instructors rather than by subject matter. There are those who make physics a port of entry to some sort of career in one of the physical sciences, and there are a few misguided souls who consider that it will be the easiest way to "work off" the science requirement.

With whatever varying degrees of satisfaction these groups may pursue their courses, there is another occasion for the study of physics which is at least as worthy as any of the foregoing and which, under proper guidance, can scarcely fail to furnish a degree of satisfaction fully worthy of the basic ideal of a liberal arts education. The greatest significance of the study of physics lies in the fact that it possesses some intensely human values. The study of physics can be made to disclose some of the principal clues to the way men think today. It was in physics that the *scientific idea* had its first development and it is in physics that the idea is today to be found in its clearest and most vigorous form. While the utilitarian aspects of the subject are not to be despised, their significance lies not so much in the multiplicity of devices which makes the daily routine so different from what it was a century ago, as in the subtle conception which gave these gadgets birth and which is vastly encouraged by their use, *the conception that the world is knowable.*

Physics is pre-eminently qualified, above all the other sciences, to illustrate this fundamental aspect of the general intellectual enterprise. Physics has clear and overwhelming priority in having shaped the prevailing modes of thought of this, the scientific era. Attaining its majority in the sixteenth and seventeenth centuries, after sporadic developments covering more than two milleniums, physics immediately became the focus of all the points of view that gradually crystallized into the scientific method. In company with astronomy, which, both in principle and in practice, is a specialized department of physics, it met and withstood the full impact of authoritarianism. It thus earned the double distinction of being the pioneer in the most productive intellectual field of modern time and of being the successful champion of the scientific idea against the tremendous odds possessed by those who denied its validity, and who invoked every agency at their command to destroy it.

None of the other sciences can even remotely approach this record. The foundation of chemistry, the science which is closest to physics in subject matter, was laid by John Dalton in the early nineteenth century. It is true that some of the objectives of chemistry were vaguely foreseen by the alchemists much earlier, but it is certainly not in alchemy that the real foundations of modern sciences are to be found. Biology in its various aspects, was also a product of the early nineteenth century, geology, geography and psychology coming still later. Medicine, of course, goes far back in history, but principally as an art rather than as a science.

All of the sciences can truthfully point to many important contributions to man's intellectual development and material welfare. But none of them except physics made any contribution to the initial development, beginning more than three centuries ago, of the basic scientific concepts. There is some reason for questioning whether teachers of physics are fully aware of the tremendous advantage which physics thus possesses as a cultural subject and whether they are making the most effective use of this advantage. The accessibility of standard works on the history of physics such as those of Cajori, Crew, Heller, Hoppe, Mach, Poggendorff, and Rosenberger, supplemented by numerous scien-

tific masterpieces in translation, the outstanding collection in English being Magie's *Source Book in Physics*, puts into the hands of everyone the best of material for such an adventure in teaching.

But this is not the only point on which physics is leading the other sciences. Even more important than mere priority in developing the scientific idea is the fact that it is in physics that this idea today finds its clearest and most vigorous expression. Aside from the unique objectivity and the logical rigor of its procedure, made possible by the nature of its subject matter, physics is today examining its own axioms and the axioms of the scientific method in general, with an avidity which sets it distinctly apart from all the other sciences. This could not have been said until very lately. Indeed, for more than a century, the prevailing attitude toward any physicist who ventured to raise the slightest question about the fundamental assumptions of science had been openly one of scorn. The adjective "metaphysical" became an epithet which strongly implied "futile," if not "asinine." Now all this is changed.

Developments on the frontier of physics, especially those associated with the successive phases of the quantum theory and with relativity, have disclosed much in the structure of science that is being interpreted as self-contradictory. However unwillingly, physicists have been compelled to inquire into the limitations on the validity of their axioms. To what extent is the material universe orderly? What is the nature of such order as can be detected? Are there natural processes that lie outside of the possibility of human comprehension? What of the beginnings and of the possible end of the physical universe as we know it? All these and many other questions are being seriously faced by physicists today. They lie within the field in which philosophers have long claimed exclusive competence. There is, to be sure, much in classical philosophy that has a bearing on even the most modern aspects of physics, and physicists who make pronouncements in this field would do well to inform themselves about these contributions. But purely philosophic doctrines are often inapplicable to scientific situations, partly because philosophers so often lack familiarity with the subject matter of the sciences upon which they are generalizing. Hence has arisen the necessity for men of science themselves to initiate their own critical examination of scientific axioms. Most of these contributions today are coming from men trained in physics, though there are a few notable exceptions.

There has been wide recognition among college teachers of physics in recent years that the traditional course in general physics is not meeting the demands of the student who is seeking a general education. Almost every one of the college texts on physics appearing during the last ten years has commented on the fact and expressed various degrees of hope or confidence that the demands could be met. They will not be met, however, by the purely subtractive method of starring technical paragraphs which may be omitted and toning down the rest to the supposed intellectual level of "arts physics." Any attempt, which is based on an assumption that the ability of those who are not expecting to continue with the subject is less than that of those who are, is doomed to ultimate failure. Addition, not subtraction, should be the main objective; addition of extensive treatment of the elements which it is the glory of physics to have introduced into the intellectual world. After this, such subtractions as become necessary on account of limitation of space will take their proper subordinate place. Besides its obvious appropriateness to the liberal arts ideal, this possesses the strategic value of taking advantage of the enormous lead which physics has over the other sciences in historical priority and philosophic depth.

There is another consideration which suggests the advisability of broadening the scope of the general physics course. Only a handful of the students in a beginning course are prospective "majors" in the subject. For the great majority, the beginning course constitutes the only curricular experience in that field. Notwithstanding this, in the usual design of first-year college courses, primary consideration is given to laying the best possible foundation for future work in the subject. The temptation to do this is quite understandable, in view of the fact that college teachers are primarily subject-matter specialists and only secondarily educators. With the best will in the world, even in the case of one who

resolutely puts behind him all conscious consideration of professional recognition and advancement, it is very difficult, against this background, to give the same heartiness of effort to the nonspecialist majority that is spontaneously lavished on the specialist minority. This does not, however, justify the prevalent practice of subordinating the legitimate and honest interests of the majority to those of the minority, which happens to include the teacher. However tempting such a practice may be, it is certain ultimately to produce a disastrous reaction against the sciences, some indications of which are already looming. To formulate the story of physics in terms of the great human values out of which it grew and which inhere in it today more strongly than ever, should constitute, not a stricture on one's teaching, but a magnificent opportunity.

It is, moreover, questionable whether the traditional general physics course, confined as it is almost exclusively to the technical aspects of the subject, is the best preparation for even budding physicists. To cite a parallel case, there is much current insistence that engineers who are unfamiliar with the economic and the sociological aspects of their profession, or who do not comprehend the implications of modern industrialism, are not adequately trained for any except minor responsibilities. In the same way, it is a grave question whether a physicist who lacks familiarity with the circumstances surrounding the creation of the fundamental concepts of his science and with the effect which the growth of these concepts is having on general modes of thought, and on economic and social conditions, will ever be capable of entertaining anything more than a restricted and provincial view of even the technical parts of his subject. If there were any doubt about the value of a liberalized approach to the subject of physics, the doubt actually would seem to be less for the budding physicist than for the casual student.

This circumstance renders even less desirable than it might otherwise seem, the common practice of segregating physics students at the beginning of the year into two groups, presenting to the one group, a purely technical course, and to the other, a purely "cultural" course. This practice has always placed at a disadvantage the student who, upon deciding to make his career in science or technology after he has embarked upon the course in general physics, finds himself in a dead-end section. The better solution may be to standardize on a type of course that leaves the way open for further work in the field and at the same time possesses the breadth of view desirable for technical and nontechnical student alike.

Thus both the opportunity of making a major educational contribution to the teaching of science at the college level and a desire to avoid the consequences of too restricted a view of the field of physics should conspire to stimulate teachers to place physics upon a broader base than it has possessed in the past. It will not be an easy undertaking, and the hardest part will be the education of physics teachers themselves for this task. It will have to be largely a process of self-education, for the graduate schools which are training college teachers of physics are almost exclusively preoccupied with the purely technical phases of the subject and all professional rewards go for accomplishment in this field. In the course of time, however, we shall perhaps attain the perspective on our subject that led Joseph Priestley a hundred and seventy years ago to write in his *History of Electricity:*

> *From Natural Philosophy have flowed all those great inventions, by means of which mankind in general are able to subsist with more ease, and in greater numbers upon the face of the earth. Hence arise the capital advantages of men above brutes, and of civilization above barbarity. And by these sciences also it is, that the views of the human mind itself are enlarged, and our common nature improved and ennobled. It is for the honour of the species, therefore, that these sciences should be cultivated with the utmost attention*

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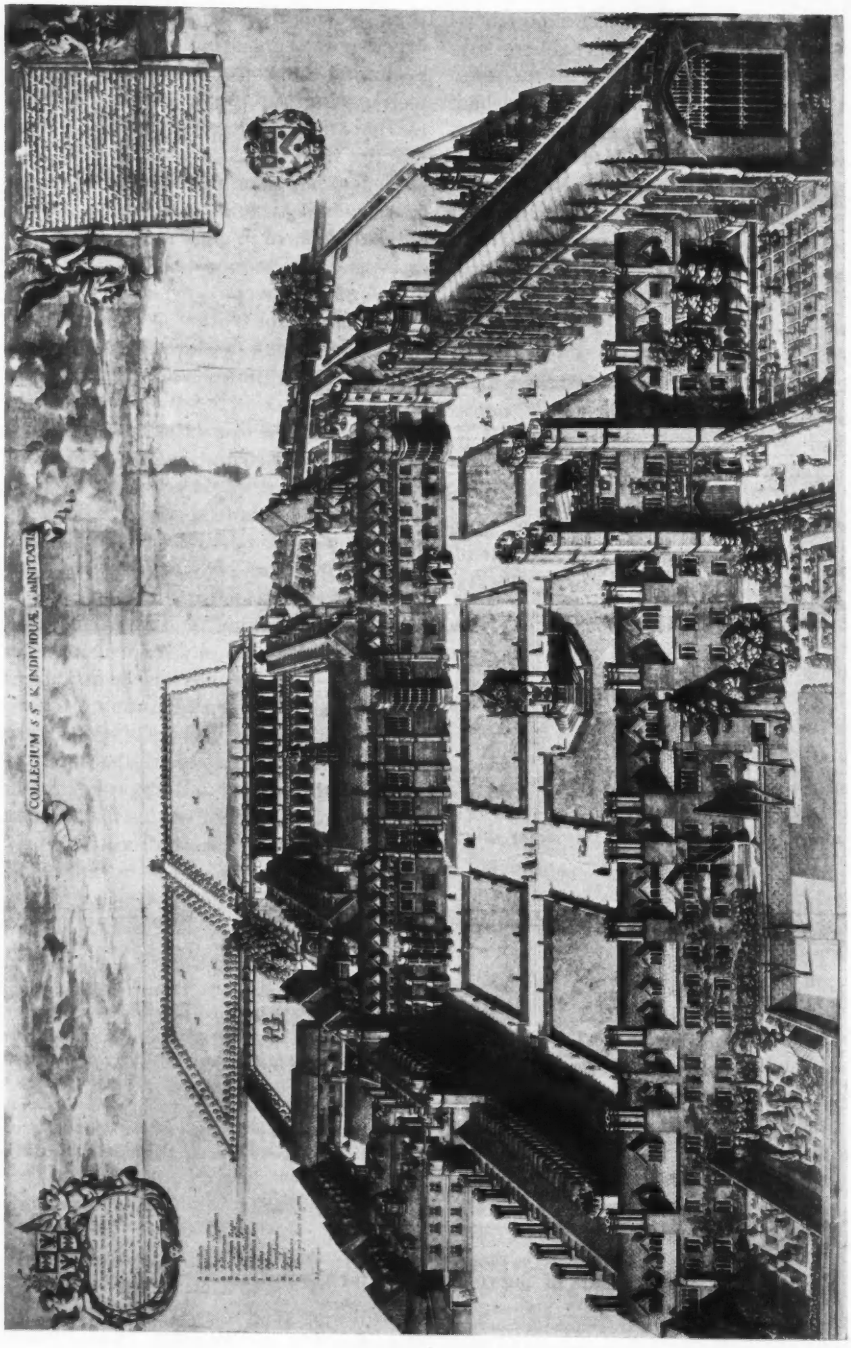

Trinity College, Cambridge, at the time of Newton
(From an engraving by David Loggan)

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

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4. Trinity College, Cambridge, at the Time of Newton

THE years 1685 and 1686 will always be memorable in the history of science, for it was during these years that ISAAC NEWTON created, *de novo*, almost the whole of his monumental *Philosophiae Naturalis Principia Mathematica*, a work characterized by the great LAPLACE as the supreme exhibition of individual intellectual effort in the history of the human race. What were the physical surroundings in which NEWTON worked during these years? Fortunately they have been beautifully and accurately portrayed in the contemporary engraving of Trinity College, Cambridge, here reproduced.

DAVID LOGGAN (1635–1693?), an artist and engraver of real merit, after twelve years of careful work, published in 1690, under the title, *Cantabrigia Illustrata*, a series of engraved views of the colleges comprising the University of Cambridge. This work was begun in 1678 or 1679 and the bird's-eye view of Trinity College might well have been executed at just the time NEWTON was writing the *Principia*. The original is a magnificent folding plate, 31×19 in., abounding in details "which speak eloquently of the time when a college was the home of its inmates, who found within the precincts all things needful for their daily life, in study, exercise, and diversion."

The rooms occupied by NEWTON were on the second floor of the entry to the right of the Great Gate as one enters the Great Court. They consisted of a room equipped as a chemical laboratory in addition to the living quarters. A flight of stairs led from one of the windows to the small garden laid out between the rooms and the street. NEWTON mounted one of his reflecting telescopes at the head of these stairs. The garden seems to have been reserved for his private use.

While the beauty of DAVID LOGGAN'S views of the colleges is readily recognized, it is not so well known that their fidelity and accuracy are also extraordinary. LOGGAN drew nothing but what he saw. A remarkable instance of this, in the view here reproduced, is pointed out by J. W. Clark, late Registrary of the University, in his 1905 reprint of the *Cantabrigia Illustrata*. He writes,

> In the right upper corner [of the Great Court], between King Edward's Gate and the Master's Lodge, a dog is barking at a large bird, in the presence of a man, presumably the dog's owner. For once, I thought, Loggan had drawn on his imagination. Not a bit of it. In searching the Audit-books for a different purpose I found, in the year ending at Michaelmas 1684, when Loggan, as I have shewn, might very likely have been working in the college, payments for 'a perch for the eagle,' 'a chain for the eagle,' and the like.

The eagle was actually a contemporary of NEWTON'S.

Valuable first-hand information regarding NEWTON and his mode of life at the time he was writing the *Principia* is given in two letters written by HUMPHREY NEWTON (no relative of ISAAC), who was NEWTON'S assistant and amanuensis from 1685 to 1690. These letters, written in 1727/8 to JOHN CONDUITT, NEWTON'S nephew by marriage, who was collecting material for a life of his uncle, have been reproduced in full in L. T. MORE'S *Isaac Newton, A Biography* (Scribner's, 1934) pp. 246–251. Only such parts, therefore, as give information regarding NEWTON'S living quarters will be quoted here.

> He was very curious in his garden, which was never out of order, in which he would at some seldom time take a short walk or two, not enduring to see a weed in it. On the left end of the garden was his laboratory, near the east end of the chapel, . . .
>
> Near his elaboratory was his garden, which was kept in order by a gardner. I scarcely ever saw him do anything as pruning, etc., at it himself. When he has sometimes taken a turn or two, has made a sudden stand, turn'd himself about, run up the stairs like another Archimedes, with an εὕρηκα fall to write on his desk standing without giving himself the leisure to drew a chair to sit down on. At some seldom times when he designed to dine in the hall, would turn to the left hand and go out into the street, when making a stop when he found his mistake, would hastily turn back, and then sometimes instead of going into the hall, would return to his chamber again. . . . His telescope, which was at that time, as near as I could guess, was near 5 foot long, which he placed at the head of the stairs going down into the garden, butting towards the east.

Hydrodynamic Model for Demonstrations in Radioactivity

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ONE of America's leading physicists, when referring to a violin, once said: "It is strange how a funny-shaped wooden box with funny-shaped holes in it, strung with the insides of a cat and stroked with a horse's tail, can emit such beautiful sounds." Here, in Fig. 1, we have several funny-shaped boxes, which have the interesting property that they illustrate the laws of radioactive disintegration and of the subsequent building up of disintegration products. The volumes of the water in the containers at any time may be regarded as the corresponding amounts of radioactive elements, and any of the well-known equations associated with radioactive accumulation and decay may be experimentally illustrated. Also the conditions of transient and secular equilibriums can easily be shown.

Shape of the Containers

To determine the shape of the containers, we start with the condition that the rate of decrease of the radioactive material is equal to a constant times the amount of material present. This gives the equation:

$$-dV/dt=\lambda V=av=ka(2gh)^{\frac{1}{2}}, \qquad (1)$$

where λ is the constant of disintegration, V, the volume, a, the area of the orifice, v, the speed of flow, g, the acceleration due to gravity, h, the height of the water, and k, a constant. From Eq. (1) we have $V=(ka(2g)^{\frac{1}{2}}/\lambda)h^{\frac{1}{2}}=2Kh^{\frac{1}{2}}$, where K is a new constant. The cross-sectional area of the container must be a function of the height h and we can write $V=\int_0^h A\,dh=\int_0^h f(h)dh=2Kh^{\frac{1}{2}}$. Differentiation yields $A=f(h)=K/h^{\frac{1}{2}}$. Thus the cross section of the container must vary inversely with the square root of the height. This condition is satisfied by letting one of the sides have the shape $x=c/y^{\frac{1}{2}}$.

The size of the container is optional, but the particular ones here described are 10 in. on the straight sides. The curved side has the shape $x=7.07/y^{\frac{1}{2}}$, which gives a value of 10 in. for x when y equals 0.5 in. Obviously the apparatus cannot give good results after the water level falls below 0.5 in. because the tank, instead of extending to a great distance, is cut off at this point. Even if it were not cut off here, the results obtained below this water level would not be very dependable because of the difficulties of leveling the tank and of getting the proper orifice at the proper level, and because of surface tension, which plays an important part at these low levels. For the tanks used the results were good down to a water level of 1 in.

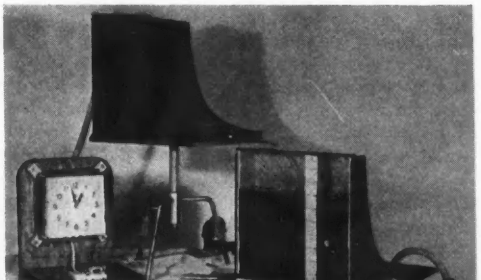

Fig. 1. Photograph of apparatus. A small amount of nigrosine was added to the water before the photograph was taken.

Construction

The tanks can be constructed in any laboratory. The base and ends are made of $\frac{1}{16}$-in. flat brass. The curves of the end pieces were formed by first marking with a paper template, and then sawing and filing to shape. The curved side, of $\frac{1}{32}$-in. brass sheet, was then forced into position by wooden forms and soldered. The glass front is held by brass cleats and made leakproof by painting the inner joint with quick-drying enamel. The orifices or nozzles are interchangeable and of various sizes to correspond to different values of λ. They were made by flattening the ends of brass tubing, inside diameter 0.5 in. and length 3 in., and bending the flat ends so that the middle of the orifices are on a level with the bottoms of the tanks.

When several tanks are used in series, the

volumes must be used to represent the corresponding amounts of radioactive materials, but for one tank alone, either the height or the volume may be thus used. To find the ratio between the constants λ_h and λ_v, differentiate the equation $V=2Kh^{\frac{1}{2}}$ with respect to time. Thus, $dV/dt=(K/h^{\frac{1}{2}})dh/dt$. But $dV/dt=-\lambda_v V$ and $dh/dt=-\lambda_h h=-\lambda_v Vh^{\frac{1}{2}}/K=-2h\lambda_v$. Therefore $\lambda_h=2\lambda_v$.

Disintegration Constants

In Fig. 2, $\log_e V$, $\log_e h$ and h are plotted against the time. From the $h-t$ curve the half-value period is found to be 73.0 sec. Using the value of λ_h found from the $\log_e h-t$ curve and employing the equation $T=\log_e 2/\lambda_h$, we find the half-value period to be 73.3 sec, which

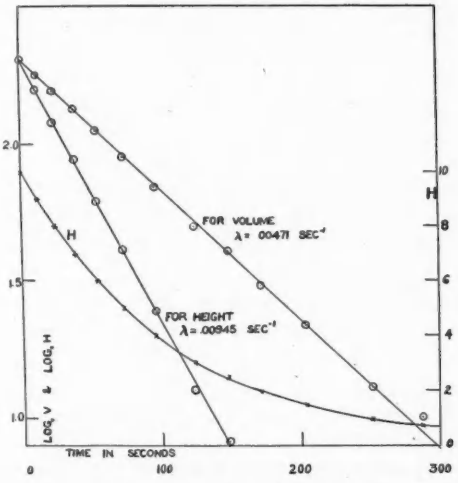

Fig. 2. $\log_e V$, $\log V_e h$, and h plotted as functions of t, using observed data.

agrees with the first value within the limits of experimental error. Also, from the curves we find that $\lambda_h=2\lambda_v$.

Data for three different nozzles are plotted in Fig. 3. As in the two preceding curves the negative of the slope of the semilogarithmic curves is equal to the constant of disintegration. The approximate sizes of the nozzles and corresponding values of λ are:

(1) $\frac{1}{16}\times\frac{13}{16}$ in., $\lambda=0.00940$ sec^{-1};
(2) $\frac{1}{32}\times\frac{13}{16}$ in., $\lambda_1=0.00471$ sec^{-1};
(3) $\frac{1}{32}\times\frac{1}{2}$ in., $\lambda_2=0.00300$ sec^{-1}.

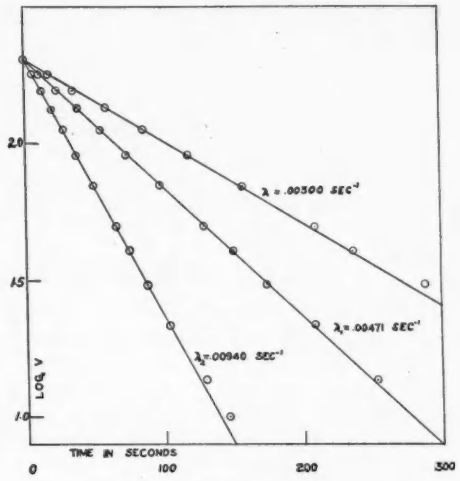

Fig. 3. $\log_e V$ *vs.* t for three different nozzles.

Nozzle No. 3 was formed by compressing the sides of the flat portion of one similar to No. 2, thereby reducing the length of the orifice from $\frac{13}{16}$ to $\frac{1}{2}$ in.

Transient equilibrium. Transient equilibrium is given by the equation $N_2=N_1\lambda_1/(\lambda_2-\lambda_1)$, where $\lambda_2>\lambda_1$. When this equation is satisfied, the rate of decay of N_2 is determined by λ_1 because the coefficient of $e^{-\lambda_2 t}$ vanishes in the equation

$$N_2=N_1{}^0\left(\frac{\lambda_1}{\lambda_2-\lambda_1}\right)e^{-\lambda_1 t}+\left[N_2{}^0-N_1{}^0\frac{\lambda_1}{(\lambda_2-\lambda_1)}\right]e^{-\lambda_2 t}.$$

When λ_1 is 0.00471 sec^{-1} and λ_2 is 0.00940 sec^{-1}, the ratio between N_1 and N_2 for transient equilibrium should be unity, very nearly. With $N_1{}^0=N_2{}^0$, the results in Fig. 4 show that N_2 is decaying (or perhaps decreasing) at a rate determined by λ_1.

Special case for $\lambda_1=\lambda_2$. The general equation for the amount of a daughter substance present at time t is

$$N_2=N_1{}^0\frac{\lambda_1}{(\lambda_2-\lambda_1)}(e^{-\lambda_1 t}-e^{-\lambda_2 t})+N_2{}^0e^{-\lambda_2 t}.$$

For the special case where $\lambda_1=\lambda_2$ this takes on an indeterminate form. By differentiating the numerator and denominator of $(e^{-\lambda_1 t}-e^{-\lambda_2 t})/(\lambda_2-\lambda_1)$ with respect to λ_1 and then placing $\lambda_1=\lambda_2=\lambda$,

the general equation reduces to

$$N_2=(N_1{}^0\lambda t+N_2{}^0)e^{-\lambda t}.$$

Starting with $N_1{}^0=10.00$ units, $N_2{}^0=5.50$ units, $\lambda_1=\lambda_2=\lambda=0.00470$ sec^{-1}, and $t=90$ sec, we obtained the results,

$$N(\text{calculated})=6.36 \text{ units},$$
$$N(\text{observed})=6.32 \text{ units}.$$

It should be mentioned that the unit of volume is arbitrary and of such size that the tank contains 10 units when full. The actual volume of each tank used is 7.34 l. This, of course, includes the theoretical volume of the part cut off. The tanks could easily be constructed to have a capacity of 10 l in which case the size of the arbitrary unit would be 1 l.

Primary source remains constant and supplies at a constant rate. For the final case we take the condition that the primary source remains constant and thus supplies at a constant rate for the time under consideration. (E.g., Ra→Rn→Ra A.) This can easily be accomplished by siphoning water from a tank that is kept at a constant level by having it overflow. Any container will serve for this purpose. The rate of supply can be changed at will by raising or lowering the hose used in siphoning. This output is caught in one

TABLE I.

($t$sec)	N(calc.)	N(obs.)
60	8.84	8.80
120	7.92	7.88
180	7.25	7.25

of the specially constructed tanks and the output of the latter goes into another of these tanks. The following equations hold:

$$N_1\lambda_1=\text{constant},$$

$$N_2=N_2{}^0e^{-\lambda_2 t}+\left(N_1\frac{\lambda_1}{\lambda_2}\right)(1-e^{-\lambda_2 t}),$$

$$N_3=N_3{}^0e^{-\lambda_3 t}+N_2{}^0\left(\frac{\lambda_2}{\lambda_3-\lambda_2}\right)(e^{-\lambda_2 t}-e^{-\lambda_3 t})$$
$$+\left(N_1\frac{\lambda_1}{\lambda_3}\right)\left(1+\frac{\lambda_3}{\lambda_2-\lambda_3}e^{-\lambda_2 t}+\frac{\lambda_2}{\lambda_3-\lambda_2}e^{-\lambda_3 t}\right).$$

When λ_2 is 0.00300 sec^{-1}, λ_3, 0.00470 sec^{-1}, $N_2{}^0$, 8.35 units, $N_3{}^0$, 10.00 units, then $N_1\lambda_1$ is 0.0222 unit sec^{-1}. The results appear in Table I. $N_1\lambda_1$ was determined by first establishing secular equilibrium and then making use of the equation $N_1\lambda_1=N_2\lambda_2=N_3\lambda_3$.

These examples are but a few of the many different cases and conditions that might be imposed. The results deviate from the calculated results by less than 1 percent in all cases where

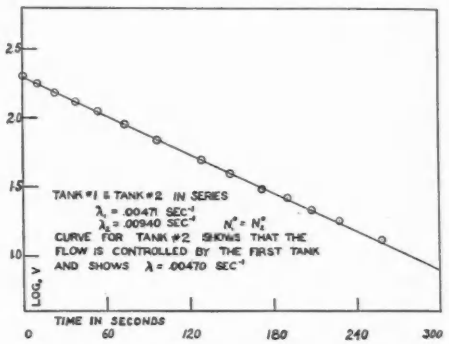

FIG. 4. Log$_e$ V *vs.* t for transient equilibrium.

the water is not allowed to fall below 1 in. Where the time is large, the tanks may be allowed to build up from zero level and any error that will be introduced for the shorter times will become negligible as the time increases. For example, the tanks will arrive at secular equilibrium when supplied by a constant source regardless of the initial conditions.

The writers found that the apparatus, although designed for demonstration purposes, can be used in student manipulated experiments. The student can determine analogs of the constant of disintegration, the half-value period, and the average life; and may verify experimentally the equation for secular and for transient equilibrium, and for the amounts of successive transformation products at any time t starting with any given initial conditions.[1] Some of these experiments would be extremely difficult and would require considerable time and preparation if they were performed with radioactive ma-

[1] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances* (Macmillan), p. 10 ff.

terials. Furthermore, the accuracy of the results are equal to, or better than, those obtained with radioactive materials unless extremely refined methods are used. Here the difficulty of having mixtures of successive products is avoided, any initial conditions are easily satisfied, and the apparatus is ready for instant use. The only auxiliary apparatus required is a clock or stop watch and a sink with faucet.

We wish to thank Mr. H. H. Kramer for his valuable assistance in the construction of the apparatus.

On Imaginary Time in Special Relativity

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THE Lorentz invariant interval,

$$c^2ds^2=c^2dt^2-(dx^2+dy^2+dz^2), \qquad (1)$$

is usually introduced by the statement that it is required by the observed invariance of the laws of the electromagnetic field. The analogy with four-dimensional geometry is then pointed out, but the beginner usually boggles at the acceptance of imaginary time required for the actual working out of this geometrical analogy. The object of this note is to suggest an approach that avoids this difficulty instead of accepting it as one of the mysteries of the Minkowski world.

The state of mind of too many students of relativity is, unfortunately, like that of the youth who first learns of algebraic imaginaries as mysterious devices which permit handling of otherwise intractable (and, in any case, physically meaningless) solutions of equations like $x^2+4x+5=0$. He may later learn that "i" can be defined as a turning operator, but never really appreciates the connection between this and the algebraic root of negative unity.

In the same way it does not appear to have occurred to anyone that the mysterious imaginary in the Minkowski interval is nothing but a turning operator.[1] It is fairly well recognized that the only safe way to teach complex number theory is to employ the operational point of view right from the beginning. It is rather amazing, therefore, that this modern point of view should have failed to clear up the status of imaginary time in the domain of relativity, the subject which has done so much to popularize that point of view. This is the more remarkable in that the answer proves to be almost obvious once the question has been formulated.

The question we wish to discuss is: Why does the Minkowski (four-dimensional) relativity interval include a turning operator among its components?

The conscious experience of any one observer is one-dimensional, in the sense that conscious attention to one detail precludes the conscious attention to any other detail. We are not asserting that the detail in question is in fact without extension or content, but that this extension may be ignored by relativity theory in building up the reference system for the space-time continuum. The only dimension immediately cognized is that known as the time dimension; there is always a lapse of time as we switch our attention from one detail to another of our sense experience. This experience lies entirely along the time track of the observer, and is thus essentially one-dimensional. Distances in any other dimensions are derived by abstract processes of measurement which are in fact all projections

[1] In his *Relativity, A Popular Exposition*, Einstein frankly states that we merely introduce $\sqrt{-1}cdt$ to get a convenient four-dimensional invariant interval. Eddington on the other hand, in *The Mathematical Theory of Relativity*, §3, tries to soothe our feelings by assuring us that this choice is no more mysterious than any other possible function of dt which might have been forced upon us by the exigencies of the problem, and exhorts us not to suppose that the imaginary time has any mystical significance in the external world. Nevertheless, and with due respect to this weighty verdict, it remains a mystery; and his advice is effectively asking us to suppress our natural uneasiness when faced with the unexplained. Such advice does not help us to achieve the degree of intellectual honesty so necessary if we are to make any progress at all in this kind of quasi-philosophical problem.

from the time dimension. On the argument familiar to students of relativity, distances in space are fundamentally measured by the times taken by light signals to traverse the distances. This is practically recognized in the modern use of the red line of the cadmium spectrum as the primary standard of length. In the use of this standard we may be said to accept the period of the source as an absolute constant, and measure lengths by means of the interference patterns, which are due to the time intervals required by the light to traverse the distances measured.

Our real measures both of length and time thus reduce finally to time measures. To construct the vector space-interval from the time measure we must rotate the latter—if we accept the geometrical point of view—from the direction of time flow into the particular direction of space which we are measuring. Since there are three independent space dimensions, there will be three turning operators. Denote them by

$$\mathbf{i}_1, \quad \mathbf{i}_2, \quad \mathbf{i}_3. \tag{2}$$

Consider two different events happening at times dt apart, and at different points in space. Let the times measuring the three components of distance between the points in space be

$$dt_1, \quad dt_2, \quad dt_3. \tag{3}$$

Then the vector joining the two events will be

$$\mathbf{i}_1 dt_1 + \mathbf{i}_2 dt_2 + \mathbf{i}_3 dt_3 + dt = d\mathbf{s}, \tag{4}$$

say, where the operators turn the time measures into their respective directions in space to give the correct space vectors to which they refer.

A double application of any one of the operators gives negative unity (directed backwards along time), so that the invariant scalar product of the vector with itself, defined as the sum of the squares of its four components, will be simply

$$ds^2 = dt^2 - (dt_1^2 + dt_2^2 + dt_3^2). \tag{5}$$

Since $dt_1 = dx_1/c$, etc., this is

$$ds^2 = dt^2 - (dx_1^2 + dx_2^2 + dx_3^2)/c^2. \tag{6}$$

From this point of view it is thus unnecessary to talk about "imaginary time" as one of the four components of a Minkowski four-vector. All four components are real time intervals. The negative squares which appear in the invariant interval arise because the three space vectors are derived from their time measures by a rotation through $\pi/2$, repetition of which (for the square) produces a vector directed backwards along time.

Thus all four-vectors will be built up by linear combinations of the four base units

$$\mathbf{i}_1, \quad \mathbf{i}_2, \quad \mathbf{i}_3, \quad \mathbf{i}_0, \tag{7}$$

where the first three are the operators already introduced and $\mathbf{i}_0$ is merely the unit vector in the direction of time flow. Their operational properties can, consistently with the foregoing interpretation, be specified as[2]

$$\left.\begin{aligned} \mathbf{i}_0 \cdot \mathbf{i}_0 = 1, \quad \mathbf{i}_\alpha \cdot \mathbf{i}_\alpha = -1, \quad \alpha \neq 0 \\ \mathbf{i}_\mu \cdot \mathbf{i}_\nu = 0, \quad \mu \neq \nu, \quad 0, 1, 2, 3 \end{aligned}\right\} \tag{8}$$

From this basis, and from fairly obvious definitions of dyadics and vector areas, a complete scheme of vector analysis in four dimensions can easily be built. One interesting result of such an analysis is a dyadic notation for the Lorentz transformations. Thus, if there are two base systems $\mathbf{i}_\alpha$ and $\mathbf{i}_\alpha'$ characterized by relative velocity

$$\mathbf{u} = d\mathbf{s}/ds, \tag{9}$$

we find that

$$\mathbf{i}_\alpha' = \mathbf{\Lambda} \cdot \mathbf{i}_\alpha, \tag{10}$$

where $\mathbf{\Lambda}$ is the dyadic[3]

$$\mathbf{\Lambda} = \mathbf{I} - [1 + \mathbf{i}_0 \cdot \mathbf{u}]^{-1}(\mathbf{u} + \mathbf{i}_0)(\mathbf{u} + \mathbf{i}_0) + 2\mathbf{u}\mathbf{i}_0. \tag{11}$$

It is easily proved that $\mathbf{\Lambda}$ is self-dual and self-reciprocal, so that the lengths of all intervals remain invariant for the transformations.

[2] This negative expression for the scalar product is not an innovation; for instance, it is used consistently by Campbell in his *Course of Differential Geometry*.

[3] Unpublished work of the writer.

The Washington Meeting, December 28–30

THE American Association of Physics Teachers will meet in Washington, D. C., on Wednesday, Thursday, and Friday, December 28 to 30. The Wardman Park Hotel will be headquarters. The program for Wednesday includes an address on "The National Standards of Measurements," by L. J. Briggs, President of the American Physical Society, an inspection of the standards in the National Bureau of Standards, and the annual dinner. The Thursday and Friday sessions will be devoted to contributed papers, exhibits, an address by P. W. Bridgman on "Society and the Intelligent Physicist," a symposium on "The Physicist in the Government Service," the presentation of the annual award for notable contributions to teaching, and the annual business meeting.

Special Commutator for the Comparison of Capacitances

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THIS method of comparing capacitances consists essentially in charging two condensers by means of a potentiometer and then testing for equality of charges by connecting them to a galvanometer. Usually the operation is carried out by means of a double-pole, double-throw switch; and, unless the two charges are equal, a momentary deflection is observed in the galvanometer. In the present method a steady deflection of the galvanometer as an indication of lack of balance is secured by introducing a rotating commutator which produces a rapid charge and discharge.

As shown in Fig. 1 (a), two circular monel rings F and H, and the flat monel segments A, D, and E are mounted on an ebonite cylinder. Small insulated monel segments are placed between the large segment E and the smaller segments A and D. The brushes L, M, N, O, and P are made of phosphor bronze with small curved strips of monel at the top, Fig. 1 (b), which make contact with the commutator sections. Better results are obtained by using monel segments with intervening open spaces between the metal sections of the commutator rather than by filling the spaces with insulating material. With this method of construction there is little danger that the brushes will ruin the insulation between the segments, as the actual insulating spaces are never in contact with the brushes. It was found advantageous to use a few drops of oil on the segments. The rings F and H are electrically connected to A and D, respectively.

The external electrical connections are shown in Fig. 1 (a). Two resistance boxes R_1 and R_2 are connected in series to the terminals of a reversing switch RS, so that their circuit positions relative to O and P can be interchanged. With the commutator in the position indicated in the figure and the reversing switch turned toward the resistance boxes, brush P connects through ring F and segment A to brush L, and brush O connects through to brush M. The condensers C_1 and C_2 are charged positively and negatively, respectively, their potentials being proportional to the ratio of the resistances R_1 and R_2. A rotation of half a turn of the commutator disconnects the condensers from the battery and connects them together, sending the resultant charge through brush N into the galvanometer G. If $C_1R_1 = C_2R_2$, there will be no deflection of the galvanometer. If this condition is not fulfilled and the commutator is rotated rapidly, a steady deflection is registered.

To test its operation, the commutator was rotated by means of a variable speed Cenco rotator. A 90-v radio battery was employed for

TABLE I. *Test for sensitivity.*

C_1 (MF)	C_2 (MF)	R_1 (OHM)	R_2 (OHM)	Av R_2 (OHM)	R_2/R_1	VARIATION BETWEEN C_1/C_2 AND R_2/R_1 (PERCENT)
0.3	0.6	8000	3997 4007	4003	0.5004	0.08
.2	.2	8000	8003 8005	8004	1.0005	.05
.2	.1	4000	8000 7996	7998	1.9995	.025
.1	.1	8000	8006 8010	8008	1.001	.1
.05	.05	8000	8020 8014	8017	1.002	.2

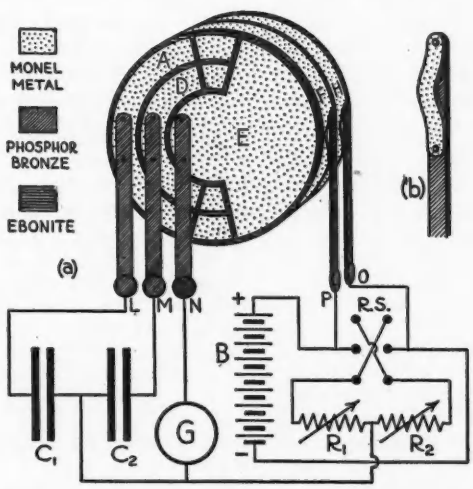

FIG. 1. End view of commutator and diagram of circuit

B, two decade condensers for C_1 and C_2, and a Weston table galvanometer of sensitivity 0.25μ amp for the indicator of balance. The speed of rotation was about 40 rev/min. Typical results appear in Table I. For each test two sets of readings were made, corresponding to the interchange of resistances. The accuracy of the values obtained corresponds very well with the accuracy of the condensers and resistance boxes available for this test. The resistance boxes were not special radio types and no correction was applied for their capacitances.

The apparatus can also be employed as a Fleming and Clinton[1] commutator where the capacitance of the condenser is estimated from the potential of the charging battery, the rate of charge and discharge, and the corresponding steady deflection of a galvanometer. For this method, connections are made with an appropriate set of three of the brushes. Tests made according to this method, employing a Weston table galvanometer of sensitivity 0.10μ amp and a speed of rotation of 20 rev/sec, indicated an accuracy of 1.5 percent for condensers with capacitance values as low as 0.0014 mf.

The method of comparing capacitances as described in this paper has been found particularly valuable as a means of calibrating laboratory standards in terms of a precision standard. The chief advantages gained by employing the special commutator in place of a double-pole, double-throw switch are that a less sensitive galvanometer is required, and the effects due to absorbed charges are minimized.

[1] Fleming and Clinton, Phil. Mag. **5**, Ser. 6.

Measurement of Flux, Flux Density and Magnetic Moment in a Magnet

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THE laboratory experiment giving an estimate of the distribution of magnetism in a bar magnet, and performed by slipping the magnet through a coil and noting the ballistic galvanometer deflection, is well known.[1] The value of determining the supposed distribution of poles by this method may be questioned. On the other hand, the method readily yields reasonably accurate values of flux and flux density as a function of position along the magnet; and from the curve obtained by plotting values of flux obtained somewhat more carefully, the magnetic moment of the magnet may be found.

The modified method consists in shifting the magnet in (quick) consecutive 1-cm steps through the coil from position (1), where the flux is sensibly zero, to the corresponding position (2), Fig. 1, and obtaining the galvanometer deflection for each step. To reduce the galvanometer error, which becomes cumulative, the average of direct and reverse readings is taken. The charge q induced by a shift in position of the magnet is given by

$$q = Ks = n\delta\phi/10^8R = nA\,\delta B/10^8R, \qquad (1)$$

where s is the galvanometer scale deflection, K its ballistic constant,[2] $\delta\phi$ the change in flux in maxwells, R the resistance of the circuit, A the area of the coil, n the number of turns, and δB the increase in magnetic field (flux density) at the coil due to the magnet. As the magnet is moved step by step, the flux at any point is the algebraic sum of all the previous changes in

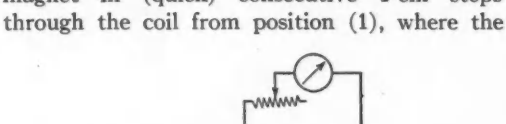

FIG. 1. Diagram of circuit, showing initial (1) and final (2) positions of magnet.

[1] Millikan and Mills, *Electricity, Sound and Light*, pp. 137–140.

[2] $K = kT_0e^{\rho}/2\pi$, with the current-constant k expressed in amperes per scale deflection s. When the open circuit damping is not excessive, the open circuit period may be used for T_0, since damping then has so small an effect on the period; while it is convenient to use the galvanometer heavily damped and to read, on a graph posted in the laboratory, the value of the damping correction e^{ρ} for the value of ρ found from the square root of the average of s_1/s_3 and s_2/s_4. The quantities s_1, s_2, s_3, s_4 are consecutive alternately positive and negative deflections. The resistance of the circuit is readily adjusted to make the value of ρ^2 lie between 2 and 4. $x = (\lambda/\pi)\tan^{-1}\pi/\lambda$ with $\lambda = \log_e \rho$.

flux; that is,

$$\phi=\Sigma\delta\phi=(10^8RK/n)\Sigma s \text{ maxwells.} \quad (2)$$

Fig. 2 shows the distribution of flux in the magnet as computed from Eq. (2).

The similar curve for the total field (flux density) B averaged over a cross section, found by dividing values of ϕ by A, corresponds more closely to the diagrams of total magnetic lines in a magnet, and to the frequent statement that these magnetic lines are always closed loops, than does the curve obtained by plotting the galvanometer deflections directly.[1] One may estimate the distribution of amperian current and intensity of magnetization by observing in Fig. 2 the concentration of flux near the center of the magnet, and remembering that, as in the case of the solenoid, the field extends out beyond the end.

The magnetic moment is found from the area under the curve in Fig. 2. The torque L on any coil or solenoid in a magnetic field B is $niAB\sin\theta$, whence its magnetic moment M is niA. Likewise the magnetic moment M of the ideal uniformly magnetized magnet may be expressed as n_mi_mA, where n_mi_m is the sheet of amperian current around the surface of the magnet. Here n_m is the number of disk-shaped layers of atoms, i_m is the current around each such cross section one atom thick, and n_mi_m is then the resultant of all the orbital or spin electron currents within the iron. The magnetomotive force, or "work to carry a pole around a current" (or to carry it from $-\infty$ to $+\infty$ through a coil), is $\Sigma H\delta l=4\pi i$. Similarly for a uniformly magnetized rod in a solenoid, $\Sigma B\delta l=4\pi(ni+n_mi_m)$, and more generally still, $\Sigma B\delta l=4\pi\Sigma i+4\pi\Sigma i_m$, even when i_m is not the same around the periphery of each of the n_m cross sections, and even if i_m extends into the iron to correspond to non-uniform magnetization in a cross section. In the special case of a magnet where the conduction current i is zero and B_m, the field of the atoms, is equal to B,

$$\Sigma B_m\delta l=4\pi\Sigma i_m. \quad (3)$$

Then

$$\Sigma B_m\delta lA=\Sigma\phi\delta l=4\pi\Sigma i_mA=4\pi M,$$

whence

$$M=\Sigma\phi\delta l/4\pi=(\text{area under }\phi\text{-curve})/4\pi. \quad (4)$$

The area under the curve may be found either with a planimeter or by constructing a trapezoid with altitude equal to the maximum flux and with sides drawn tangent to the curve. In the latter case the area under the curve is compared with the area of the trapezoid by counting the small squares in the corners.

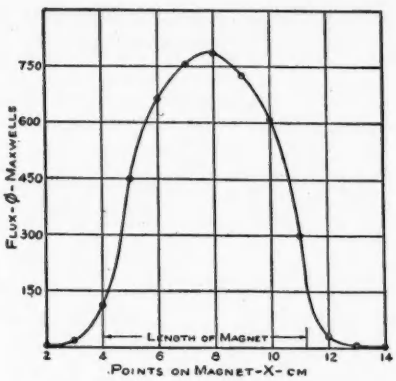

FIG. 2. Distribution of magnetic flux along a magnet.

The foregoing brief theory gives expressions for amperian currents by analogy with the solenoid. It is easy to apply the same ideas directly to the atoms. An electron with period τ in an orbit of area A_e is a current e/τ giving the atom a magnetic moment $eA_e/c\tau$, with a component $eA_e\cos\theta_e/c\tau$ along the direction of magnetization. The sum of these projected moments, $\Sigma eA_e\cos\theta_e/c\tau$, over a cross section of area A may be set equal to i_mA, thus defining the amperian current i_m around the periphery of the cross section. If the alignment of atoms is greater in one part of the area A than in another, the expression $M=i_mA$ gives the correct effect at distances large compared to the diameter of A, but gives it less accurately at nearer points. In any case A can be limited to the region for which the intensity of magnetization is uniform. If, for example, a round bar magnet is more strongly magnetized near its axis, the amperian current around any cross section one atom thick is made up of a part around the periphery corresponding to the intensity of magnetization near the surface, and additional parts in smaller concentric rings corresponding to the additional magnetization inside. The line integral $\oint Bdl$ passing through any point within the orbit at any angle is $4\pi e/c\tau$, and this integral is zero if the line passes outside the orbit. Thus this expression summed over the area A is valid even when the sum of the projected orbits $\Sigma A_e\cos\theta_e$ is considerably less than A, as is the case for the unfilled shells next inside the outer shells of the atoms which are believed to give rise to ferromagnetism. For spinning electrons this projected area is still less. The double integral $\int\oint BdldA$ over the area A becomes $4\pi i_mA$, and on summing the sheets of area A for the whole magnet, $\Sigma\int\oint BdldA=4\pi\Sigma i_mA$ as in Eq. (4). When i_m is uniform throughout the

length of the magnet, or when i_m is used as the amperian current averaged over the n_m cross sections, Σi_m may be replaced by $n_m i_m$.

To obtain accurate values of ϕ and B in the magnet the test coil must be fitted so that it barely slips over the magnet; then the cross section of the coil and the magnet are practically the same. If the coil is larger, B is averaged over the cross section of the magnet plus the cross section between the magnet and the coil. However, the area under the flux curve in Fig. 2 and the magnetic moment computed therefrom are independent of the size of the test coil since there is no contribution to $\oint Bdl$ of a line not passing through the magnet.

To compare this amperian-current method with the method supposed to give a distribution of poles, the magnetic moment may be expressed as

$$M=a\Sigma(\Sigma s)\delta l$$
$$=a[s_1\delta l_1+(s_1+s_2)\delta l_2+(s_1+s_2+s_3)\delta l_3+\cdots],$$

using Eqs. (4) and (2) and letting $10^8RK/4\pi n=a$. This may be written

$$M=a[s_1(\delta l_1+\delta l_2+\delta l_3+\cdots)+s_2(\delta l_2+\delta l_3+\cdots)+\cdots]$$
$$=a[s_1l_1+s_2l_2+\cdots+s_il_i+\cdots]. \quad (5)$$

Here l_i is the sum $\Sigma\delta l$ reckoned from the position of the coil, where any deflection s_i is taken, to any point chosen as axis; for example, the magnetic center of the magnet. In practice $\delta l_1=\delta l_2=\delta l_i$ may be made 1 cm. In Eq. (5) s_1 is not the deflection obtained by slipping the magnet from position (1) to position (J), where its end is within the coil (Fig. 1), but is that produced by the 1-cm shift from position (1). Since the changes in flux and the galvanometer deflections are additive, it is clear that the sum of the products s_il_i give too small a value of M when the first term is obtained by shifting from (1) to (J), as is done in obtaining the curve in Millikan and Mills,[3] The half-length of the magnet used there for l_1 is less than the proper l for any of the 1-cm shifts in the region between (1) and (J). Tests on a short magnet and a long one of the same cross section gave values for magnetic moments that were 0.5 and 3 percent less, respectively, than those obtained by the flux method. The difference depends on the distribution of magnetization, which was not the same for the two. Although this error may or may not be larger than experimental errors, it is more serious, for it arises from the assumption that the curve represents distribution of poles whereas it really is a plot of deflections proportional to changes in flux and field. Obviously the field at any position of the coil, expressed in terms of poles, is the field due to all the poles on the surface of the magnet rather than only those nearest the coil. The poles do not in general distribute themselves to give zero field in the magnet, as do electrical charges in a conductor, and the flux emerging from the end of the magnet is not exactly 4π times the pole strength there.

The foregoing method of studying the magnetism in a magnet presents the physical ideas more accurately than does the description in terms of the fictitious poles and the assumption that the galvanometer deflections represent the pole density. Besides reducing the danger of running into such an error, the amperian-current picture is much to be preferred over the polar cap picture, for it presents the description of magnetism in terms of the behavior of current in a solenoid, which the student must learn anyway, and it preserves the solenoidal character of B inside the magnet. To be sure it abandons the historical approach to the study of magnetism, but in so doing it becomes a genuine explanation —a reasonably satisfactory description of magnetism in terms of quantities, currents, already known experimentally. The invention of a separate kind of physical quantity, the pole, to "explain" magnetism does not provide a description in terms of quantities otherwise known. The amperian current is an average effect of what is believed to be the electronic currents in the iron atoms, and so can be considered just as real a current as any conduction current, which consists of some kind of average motion of electrons in a wire. This belief in the magnetic effect of the circulatory motion of charge in the atom is supported by the experiments on rotation by magnetization, and the converse; by ignoring these experiments the pole theory assumes incorrectly that magnetism has nothing to do with the rotation of charge. Polar caps are thus much more fictitious than surface currents.

The use of amperian currents is an attempt to modernize[4] the elementary description of magnetism with some degree of caution. After all, the evidence for a physically spinning electron is very slight;[5] the usual assumptions[6] made regarding the half-value of the spin angular momentum can conceivably be introduced in an equivalent fashion without mentioning physical spin, and orbit orientation in the incomplete (magnetic) 3-d shells is not disproved by x-ray evidence.[7]

[3] Reference 1, Fig. 104, p. 138.

[4] Heaps, Am. Phys. Teacher **6**, 216 (1938).
[5] Milne, Proc. Roy. Soc. **A165**, 329 (1938).
[6] For example, see Rev. Mod. Phys. **10**, 90 (1938).
[7] Yensen, Phys. Rev. **31**, 714 (1928).

A Laboratory Method for Determining the Coefficient of Diffusion of a Salt

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WHEN fluids of different kinds or concentrations are brought into contact, intermixing occurs until a uniform mixture is ultimately formed. This well-known process of diffusion is brought about by the characteristic migratory movement of fluids acting independently of gravitational forces. The phenomenon is an important factor, for example, in the control of the reaction velocity in heterogeneous systems; for the rate at which the products of the chemical reaction are removed from the interface of the two phases into the surrounding medium will be determined by the rates of diffusion of these products.

The earliest account of the study of diffusion is attributed to Berthollet (1803) who states,

> When water acts on a salt to dissolve it, the layer which is contiguous to the salt is in a state of greater saturation than that which is superposed on it, and so on until the surface is reached: there is thus only a small difference in saturation between each adjacent layer.

This statement at once suggests a close analogy between the process of diffusion and that of thermal conduction, which was confirmed quantitatively by Graham[1] in his classical experiments on the inter-diffusion of solutions. His results are expressed by a mathematical law formulated by Fick;[2] namely,

$$dn/dt = K_n \cdot d^2n/dx^2, \qquad (1)$$

where dn/dt is the rate of change of concentration at any point x where the concentration is n and the concentration gradient dn/dx, and where K_n is the coefficient of diffusion of the dissolved substance for the particular concentration n.

The nature of the force involved in diffusion was ascribed by Nernst[3] as being identical with that of osmotic pressure, the process being enormously slower in liquids than in gases on account of the larger frictional resistance. From osmotic pressure and diffusion measurements he showed that a force of 4.7×10^9 kgwt was required to drive 1 mole of cane sugar through water with a speed of 1 cm/sec. Furthermore Nernst derived a theoretical expression for the coefficient of diffusion in terms of the ionic velocities in the case of a salt dissociating into two univalent ions. There is a close agreement, for very dilute solutions, between the calculated values using transference and electrical conductivity data, and those obtained from direct measurement. The discrepancy at higher concentrations may be attributed to the increasing importance of the undissociated substance in the diffusion process. Noyes[4] extended the analysis of Nernst to the more general case of ions of any valency, and his amended formula for the diffusion coefficient is $K = RT(UV/(U+V))(1/x+1/y)$, where U and V are the respective speeds of the ions under a force of 1 dyne, and x and y are the corresponding valencies. The value of K calculated from this formula will refer to the limiting value at infinite dilution; for any other concentration the value of K as deduced from Fick's law will be greater or less than this limiting value according as the undissociated substance diffuses faster or slower than the ions. It is found by experiment that, in general, the coefficient of diffusion becomes larger as the concentration decreases; thus the ions would appear to move more rapidly than the undissociated portion.

The experimental study of the diffusion of salt molecules, in contrast to that of the ions, has been most conveniently carried out by using solvents of small dissociating powers, usually organic compounds of high molecular weight. On the theoretical side Sutherland[5] and Einstein[6] independently deduced, from kinetic theory considerations, the equation $K = RTB/N$, where K is the coefficient of diffusion of the undissociated substance in solution, R is the gas constant, T is the absolute temperature, N is the number of molecules per mole, and B is a friction coefficient. If it is assumed furthermore that the molecules of the solute are large compared with those of the solvent itself and that the diffusing molecule is surrounded by its own "sheath" of solvent molecules during its motion, then Einstein showed that under these conditions the value of

[1] Phil. Trans. Roy. Soc. **140**, 1 (1850); **151**, 183 (1861).
[2] Pogg. Ann. **94**, 59 (1855).
[3] Zeits. f. physik. Chemie **2**, 613 (1888); **4**, 129 (1889).
[4] See Haskel, Phys. Rev. **27**, 145 (1908).
[5] Phil. Mag. **9**, 781 (1905).
[6] Ann. d. Physik **19**, 18 (1906).

B is given by the simple expression $1/3\pi\eta d$, η being the coefficient of viscosity of the solvent, and d the diameter of the diffusing molecule. Inserting this value of B, the Sutherland-Einstein relation becomes $K=(RT/N)(1/3\pi\eta d)$, which is usually known as the Stokes-Einstein equation.

The validity of the Stokes-Einstein equation can be conveniently tested by employing it to determine d, and comparing this value with that obtained by an independent method, as, for example, by direct measurement of the diameters in the case of microscopically visible particles. J. H. Shaxby[7] performed experiments of this nature and obtained good agreement with theory. It also follows from the foregoing equation that $D\eta$ is constant, at a constant temperature, for the same nonelectrolyte diffusing in different solvents. Hence, provided the simple basic assumptions of the theory are otherwise satisfied, a marked divergence from this constancy serves as a probable indication of association between solute and solvent molecules. Again the Stokes-Einstein relation indicates that the temperature variation of K depends both upon the explicit change of T and upon any variation of the viscosity of the solvent, d being supposed invariable with temperature. J. D. R. and F. E. C. Scheffer[8] found good agreement in the case of aqueous solutions of mannit between 0° and 70°C, but recent experiments on the diffusion of tetrabromethane in tetrachlorethane by Cohen and Bruins[9] show a considerable divergence. The latter experiments are outside the range of applicability of the Stokes-Einstein formula, however, since the molecules of the solute and solvent are comparable in size, thus necessitating the use of a more complicated function for B.

Cohen and Bruins found that the variation of K with temperature followed an exponential relation and this result is actually in accordance with a recent theory due to Eyring.[10] This theory is based on the conception of "holes" in liquids, and implies that the velocity of diffusion of a molecule in any medium is controlled by its volume and shape rather than by its mass. A further observation made by Oholm,[11] that substances showing a high value of K have a correspondingly small temperature coefficient, and vice versa, is also in general qualitative agreement with Eyring's theory.

Numerous attempts have been made to obtain a relation between K and the molecular weight of the diffusing substance, but with only limited success. Riecke[12] deduced from the kinetic theory the relation $K=AL/M^{\frac{1}{2}}$, where A is a constant, M is the molecular weight, and L is the mean free path of the diffusing molecules; it is found to hold approximately when restricted to certain groups of substances in the same solvent.

Assuming the validity of application of the Einstein equation to small particles suspended in a solvent, Einstein has shown that the diffusion coefficient can be linked up with the theory of the Brownian movement. If the actual displacements of a given particle of radius r in the x-direction are Δx_1, Δx_2, etc. in time t, then $(\Delta x^2)_{Av}=RTt/3N\pi\eta r$, where $(\Delta x^2)_{Av}=(\Delta x_1{}^2+\Delta x_2{}^2+\cdots\Delta x_n{}^2)/n$. If this expression is combined with the Stokes-Einstein relation it follows that $D=(\Delta x^2)_{Av}/2t$. An obvious application of this theory is to the subject of colloidal solutions, and with the advent of the ultracentrifuge many interesting results have been forthcoming. By a combination of diffusion and sedimentation measurements in the ultracentrifuge, Svedberg[13] and his pupils succeeded in determining the particle radii and molecular weights of proteins.[14]

This resumé of the different aspects of diffusion suggests various indirect methods for the determination of the diffusion coefficient, when the other involved constants are known. For direct measurements of K, however, it is necessary to solve Eq. (1), except when the steady state method is employed. In contrast to the variable state method the concentration at each point of the diffusion vessel remains constant during the period of observation of a steady state experiment, which is an important advantage in accurate work when it is remembered that K is a function of concentration. Clack[15] has employed the steady state method in his investigations on the diffusivity of aqueous salt solutions, and his experiments indicate that the linear formula $K_\theta=K_{18}[1+0.026(\theta-18)]$ is accurately applicable only for temperature ranges of the order of 5°C. The purpose of the method to be described was to provide a student's experiment for the direct determination of K, and in consequence the variable state method was adopted as being more susceptible to a simple form of apparatus.

The solution of Eq. (1) is a Fourier series which, after the initial conditions of the problem have been satisfied, will enable the value of K to be determined from observations of the change of concentration with time at some particular point. The experimental difficulty of determining the concentration, or change of concentration, at any point without disturbing the liquids is at once apparent. Hence, in using a variable state method, some property of the salt solution is required that can be correlated with

[7] Comptes rendus **180**, 195 (1925).
[8] Proc. Amsterdam **19**, 148 (1916).
[9] Zeits. f. physik. Chemie **103**, **109**, **113**, **114**.
[10] J. Chem. Phys. **4**, 281 (1936); **5**, 726 (1937).
[11] Meddel. Nobelinst. **2** (1913).
[12] Zeits. f. physik. Chemie **6**, 564 (1890).
[13] J. Am. Chem. Soc. **48**, **49**, **50**, **51**, **52**.
[14] An excellent summary of the work on diffusion is given by Fürth, *Handbuch der Mechanik*, Vol. 7, and by Clack in a review entitled *On Diffusion in Liquids* (Univ. Press, Aberdeen, Scotland).
[15] Proc. Phys. Soc. Lond. **21**, **24**, **27**, **29**, **33**.

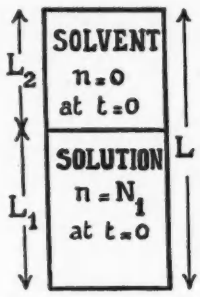

FIG. 1.

the change of concentration and at the same time can be measured without causing a disturbance. The properties that readily come to mind, and in fact have been utilized, are the density (by the use of different-density glass beads), the refractive index, and the color of a solution. In the present method it is the last property which has been utilized, by employing a photoelectric cell to measure the intensity of a beam of light after it has passed through the solution contained in a glass cell. The procedure adopted is that known as the "jar" method in which the pure solvent is carefully superposed upon the solution contained in a jar of uniform cross section.

A STUDENT EXPERIMENT

Theory.—In Fig. 1 the solution and pure solvent occupy lengths L_1 and L_2, respectively, of the "jar." The solution of Eq. (1) for the conditions imposed by this arrangement is

$$n_x=\frac{N_1L_1+N_2L_2}{L}\sum_{p=1}^{p=\infty}\frac{2(N_2-N_1)}{p\pi}\sin\left(\frac{p\pi L_1}{L}\right)\times\cos\left(\frac{p\pi x}{L}\right)\exp\left(-p^2\pi^2Kt/L^2\right), \quad (2)$$

where N_2 has to be equated to zero. Eq. (2) is obviously inconvenient for the approximate evaluation of the diffusion coefficient, but it is to be noted that the importance of the terms in the summation decreases with the larger values of p and t, so that after a certain interval of time it may be possible to neglect all terms except the first. For the particular case in which $L_1=L/2$, it also follows that the terms corresponding to the even values of p will disappear owing to the vanishing of the sine term. Hence Eq. (2) may now be written as

$$n_x=(N_1L_1/L)+(2N_1/\pi)\sin(\pi L_1/L)\times\cos(\pi x/L)\exp(-\pi^2Kt/L^2). \quad (3)$$

Two different methods of correlating Eq. (3) with the experimental observations immediately suggest themselves: (*a*) The values of the concentration n at different times are observed for any particular value of x, and in this case Eq. (3) may be re-written as

$$n_x-(N_1L_1/L)=A\exp(-\pi^2Kt/L^2), \quad (4)$$

where A is a constant. In the range of applicability of this equation it follows that a plot of $\log_e(n_x-N_1L_1/L)$ against t should yield a straight line, the slope of which is equal to π^2K/L^2. The value of K deduced from such observations evidently will only be approximately correct, since the concentration is continually varying at the given point and K itself depends upon the concentration. (*b*) In this method x is regarded as the variable and n is constant. Thus Eq. (3) becomes

$$\log_e(n_x-N_1L_1/L)=\log_e B+\log_e\cos\pi x/L-\pi^2Kt/L^2, \quad (5)$$

where B is a constant. Hence, in the region where this equation is applicable, it is easily seen that $\log_e\cos\pi x/L$ is proportional to t, and a plot of these two variables should give a straight line. The slope of this line enables the value of K to be deduced for a particular concentration.

Apparatus and experimental procedure.—The "jar" used in the experiment (*C*, Fig. 2) is a glass cell, approximately 8 cm high, 5 cm wide and 1 cm deep, made of thin uniform glass plates suitably cemented together. This cell is placed on a rigid stone pillar *D* to avoid any mechanical disturbance of the solution. The pillar itself is carefully kept free from a horizontal wooden platform *W*. A rack and pinion *R* enables this platform to be adjusted vertically and thus a beam of light from an automobile headlight bulb *B* can be passed through any required part of the "jar" and hence into the photoelectric cell *P*. Both the lamp and the photoectric cell are fixed to the platform so that they move together and

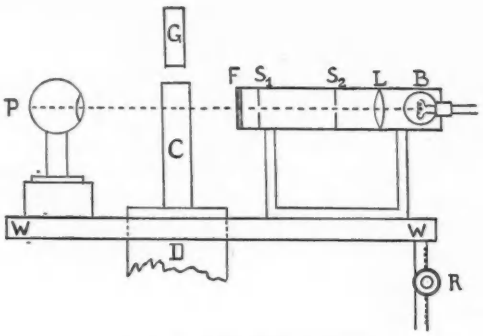

FIG. 2. Diagram of apparatus.

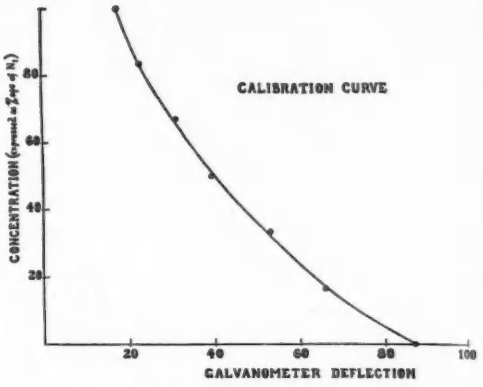

FIG. 3. Calibration curve.

thus their relative positions do not alter. The lamp B is shielded and suitably placed with respect to a collimating lens L, and the parallel beam of light emerging from the lens passes through two narrow slits S_1 and S_2 so that its width is limited to about 2 mm. A red filter F is employed to utilize the greater sensitivity of the caesium-type photoelectric cell to the longer wave-lengths. The photoelectric cell P is connected in series with a mirror galvanometer, a high voltage battery and a suitable high resistance. Since the observations extend over a number of days, it is of great importance to insure that the intensity of the light source should remain constant throughout the experiment; any variation, unless known, would make the correlation of the results an impossibility. Consequently, the current through the lamp is always adjusted approximately to the same value before each experiment with the aid of an ammeter in series with a secondary battery. Furthermore the device is adopted of using a pile of glass plates G as an invariable absorbing medium, and each set of galvanometer readings includes the deflection corresponding to that obtained on passing the beam of light through the pile of plates. Since the variation of this reference reading is quite small, the values of the galvanometer deflections in each set of observations are proportionately adjusted to correspond with a fixed reference reading.

TABLE I. *Evaluation of the diffusion constant of nickel chloride.*

METHOD	X (CM)	AV. CONC. AT X	SLOPE OF GRAPH	K (CM^2/DAY)
(a)	2.5	57	0.00141	0.51
(a)	6.0	24	.00187	.67
(b)	—	55	.00163	.57

In order to correlate the magnitude of any observed deflection with the concentration of the salt in the solution layer through which the light beam has passed, it is necessary to fill the cell with a number of solutions of suitable strengths to cover the range used during the diffusion experiment. The deflections obtained are then plotted against the corresponding concentration and a calibration curve drawn (Fig. 3).

In filling the diffusion cell the pure solvent (in this case water) is poured into the "jar" until the halfway mark is reached, and the fine stem of a tap funnel is then dipped into the water so that its tip is in close proximity to the bottom of the vessel. The solution is then allowed to run slowly from the funnel to displace the water until it finally occupies the lower half of the "jar." By this procedure the line of division between the solvent and the solution can be kept quite sharp. In each set of observations the beam of light is passed through the cell at a series of different heights, the settings being made by means of a cathetometer focused on a fixed mark on the platform W. At each height the galvanometer deflections are observed both with the lamp on and off, the difference in the readings being taken as a measure of the dilution at that particular position. This procedure is adopted as a small deflection may be obtained in the absence of the lamp. It should be mentioned, however, that external light is excluded as far as possible

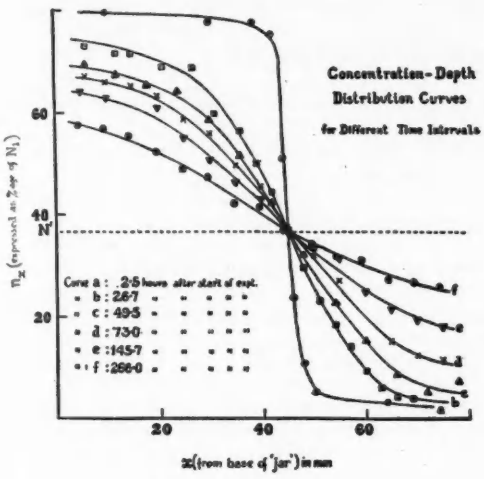

FIG. 4. Plot of n_x *vs* x.

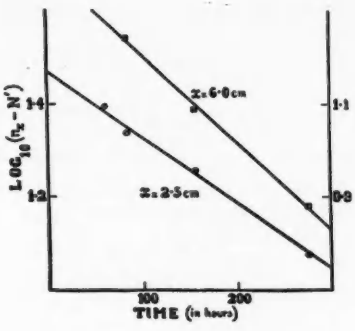

FIG. 5. Graph for method (a).

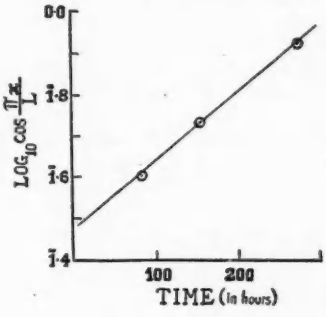

FIG. 6. Graph for method (b).

by enclosing the whole apparatus in a dark wooden box provided with a dark curtain as a covering for its open side.

The set of curves in Fig. 4 is typical of those originally obtained by Fick, the horizontal dotted line at N' indicating the final concentration of the solution when complete mixing has been affected. The resulting data and evaluation of K by methods (a) and (b) are shown in Table I, and the corresponding graphs appear in Figs. 5 and 6. The average temperature was 18°C, the initial concentration was 100, L was 8.06 cm, and the bottom of the "jar" corresponded to the reading $X=1.1$ mm. The concentration of the solution is expressed in grams of salt per liter of solution.

For a force of 1 dyne, the speed U of a chlorine ion is 7.1×10^{-16} cm/sec and the speed V of a nickel ion is 4.7×10^{-16} cm/sec. In this instance the Noyes formula becomes

$$K=(3/2)RT\cdot UV/(U+V).$$

On substitution, we obtain $K=0.88$ cm²/day at 18°C. This calculated value of K corresponds to the limiting value at infinite dilution and it therefore shows a general agreement with the experimental values in Table I. It should be emphasized that since K is a function of concentration, the simple equation of Fick used in the preceding analysis is only an approximation, and, furthermore, with the high concentrations employed there is actually the diffusion of the undissociated salt superposed on that of the ions.

Back Numbers Wanted

THE American Association of Physics Teachers will pay one dollar per copy for the February, 1933, issue of the American Physics Teacher, unbound and in good condition. Copies should be addressed to the American Institute of Physics, 175 Fifth Avenue, New York, N. Y., with the name and the address of the sender and with a covering letter.

DISCUSSION AND CORRESPONDENCE

Student Opinion of Examinations

MUCH has been said and written during the past five years with regard to the relative merits of the completion, the multiple-choice, the true-false and the essay types of examinations. In most cases the opinion has been from those who give the examinations. The writer felt that it would be interesting as well as helpful in his own course to know what the students think about these examinations.

A questionary was therefore prepared that would enable the students to express their preferences, and also their opinions relative to the reliability and validity of the four types of examinations. The students were not required to sign their names but were asked to indicate their section and year in college. The instructions were to read each of the following statements carefully and then rank the four examinations with respect to it:

1. I prefer the four types in order indicated. . . .

2. If you feel that a combination of two or more types should constitute the examination, indicate those you would include. . . .

3. The grading is most fair and best represents my knowledge of the subject as follows. . . .

4. The questions are less confusing and easier to understand in the four types as follows. . . .

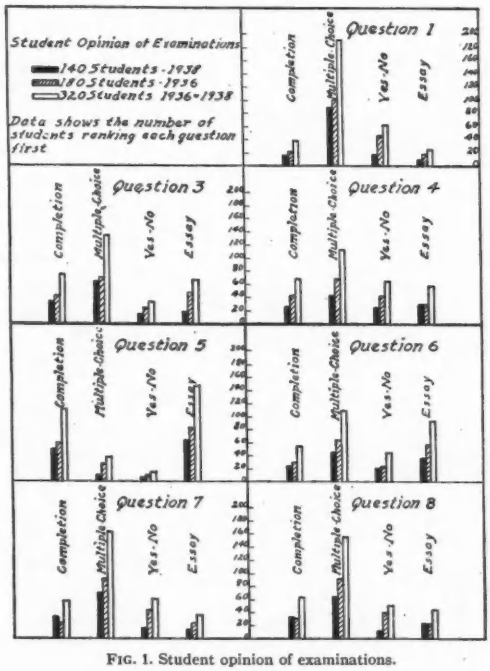

FIG. 1. Student opinion of examinations.

5. The order in which there is less tendency to guess at the answer is. . . .

6. The order in which the questions are more thought-provoking and require more reasoning is. . . .

7. The questions seem to represent best the material taken up in the course in the following order. . . .

8. The examinations function best as a teaching instrument (contribute most to my knowledge of the subject) as follows. . . .

This questionary was given to 325 students in classes in agricultural physics, 185 students in 1936 and 140 in 1938. The results are shown in Fig. 1. It will be noted that the data for the two groups, although obtained two years apart, are almost identical.

The multiple-choice test ranked highest with the majority of the students on all the statements except No. 5; namely, the tendency to discourage guessing. On this point the essay-type test naturally ranked highest.

Statements 3, 4, and 7 seek information with regard to reliability and validity. It will be noted that the majority expressed preference in No. 1 for the type which they also felt could be graded most fairly and which best represented the material taken up in the course.

The response to statement 6 is significant in view of the criticism so often made that the multiple-choice type (and the objective test in general) does not provide questions that provoke thought or require reasoning. Student opinion does not support this indictment.

Statement 2, which appeared only in the 1938 questionary, resulted in choices of so wide a variety that it does not seem worth while to discuss them.

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RUSSEL D. MILLER

An a.c. Operated Photoelectric Relay

A DEMONSTRATION of the photoelectric cell never fails to excite the interest of a class. The author has constructed several photoelectric relays and believes that physics teachers will be interested in the one described in this note.

The main feature of this relay is the use of the new 313A cold-cathode gas-filled tube.[1] As shown in Fig. 1, the tube has two conduction paths, one from the anode *A* to either of the control electrodes *B* or *C*, known as the main gap, and the other from *B* to *C*, known as the control gap. The main gap has a breakdown potential of 175 v and a sustaining potential of about 75 v. The control gap breaks down at 70 v and is sustained at 60 v. A breakdown in the control gap produces a current in the main gap when the applied voltage is above the sustaining potential. The maximum safe current in the main gap is 30 ma.

In this circuit the control voltage is the drop in potential across the resistor or condenser which is in series with the

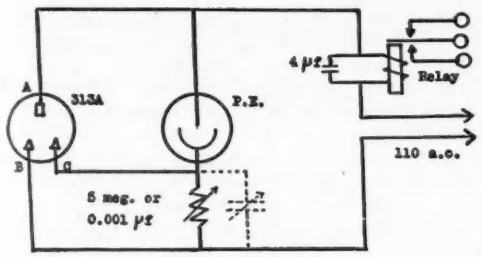

FIG. 1. Photoelectric relay.

photoelectric cell. When light falls on the cell the resulting photoelectric current raises the control potential above its breakdown value and thus produces a breakdown in the main gap. It is this current in the main gap that operates the relay. The relay current exists only when terminal A is positive.

Since the drop across the tube is nearly constant, the resistance of the relay, or any device in the anode circuit, must be large enough to limit the current to its safe value. The relay-operating current may be adjusted for various light intensities by varying the resistance or capacitance in series with the photoelectric cell. The maximum current depends also on the terminal voltage. When the terminal voltage is 110 v, a 2600-ohm relay operating on 6 ma gives satisfactory performance.

This relay eliminates the filament transformer and the power wasted in heating the filament. The relay will operate continuously on less than 3 w.

The tube, relay, and $4-\mu f$ condenser used in this apparatus were obtained through the courtesy of the Western Electric Company.

J. J. COOP

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Chestertown, Maryland.

[1] For a description of the tube, see S. B. Ingram, Bell Lab. Record 15, 114 (1936).

A Study of the Results of the Cooperative Physics Tests

AT Chicago we use the *Cooperative Physics Tests for College Students* as a part of the regular course examination. We are not only interested in comparing our scores with the national averages but, since the course is taught by a number of different instructors, these tests are the one way we have of comparing different sections. As a further use of the tests, attempts have been made to determine from them, the topics we have taught adequately and those on which we have failed. Lastly, many of the students and a few of the instructors have felt that the scores would be a better measure of the student's accomplishments if a little more time were available for each test. With these points in mind, I have been making some study of the Chicago scores.

For *Mechanics 1938 B* (Solids and Fluids) and *Electricity 1938 B*, I determined the average score for each question. When these were plotted against the serial numbers of the questions, there seemed to be such a

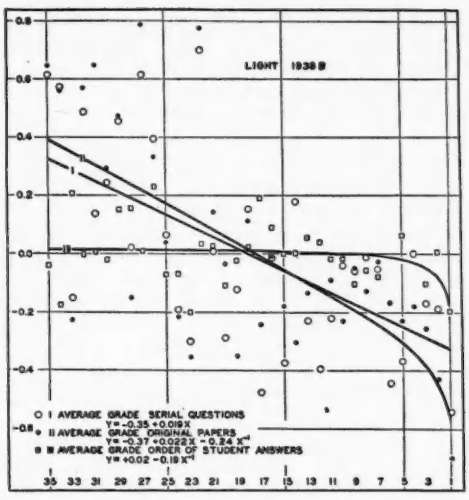

FIG. 1.

regular trend that I attempted to compute a correlation curve between grade and serial number. After trying a number of equations of the form $y=a+\Sigma b_i x^i+\Sigma c_i x^{-i}$, $i=1, 2, 3$ fitted to the data by least squares methods, and for each computing the corrected correlation coefficient, I found that the exact form was not at all critical. Most of them gave a corrected correlation coefficient ~ 0.6. A qualitative comparison of the curves with the plotted points lead me to use the form

$$y=A+Bx+Cx^{-1}$$

(see the black dots of Fig. 1, marked "Original Papers") for the correlation curve between the average grade on a question and its position in the test. The serial number x is counted from the *end* of the test. While the numerical values of the coefficients were not quite the same for different tests, the general shape of the curves seemed to be rather constant. Only *Mechanics of Solids 1938 B* was distinctly different.

Should this trend be ascribed to the order of questions chosen by the editors of the tests, or should it be ascribed to a combination of fatigue and, perhaps, panic on the part of the student as the time for the end of his writing approaches? In an attempt to answer this question, I took 120 sets (only 115 were finally used) of *Heat 1938 B* and by cutting and pasting, rearranged them into four similar groups, each consisting of 30 sets permuted in cyclic order.

The grades could then be recorded and averaged according to the serial numbers of the questions, and also according to their positions on the papers of the individual students. Fig. 2 shows the result. For grades on serial questions which had been answered at different parts of the test by different students, a straight line correlation seemed to be best (curve I, Fig. 1 and curve III, Fig. 2). For grades on questions in the order of student answers, regardless of what the question was, a curve of the form

FIG. 2.

$y=a+cx^{-1}$ seemed to be best (curve III, Fig. 1 and curve IV, Fig. 2). There was a distinct tailing off at the very end of the test, indicating that an additional minute might have been useful if it could have been added after the student thought that the time was up. However, the most of the trend is evidently due to the editor's arrangement of the questions. On this test, the serial numbers were left on the papers. While the test was rather closely proctored and no offenders noticed, it was suspected that perhaps some of the students went through their papers to No. 1 and started there.

I decided to repeat the experiment with *Light 1938 B*. This time 70 sets of questions were rearranged, 35 permuted in forward cyclic manner and 35 in backward cyclic manner. The serial numbers were *completely* removed from the questions. In addition, 34 regular papers were used. The three types were mixed together and given out at random. The results are given in Fig. 1.

The rather large standard deviation in the scores of grades, which can be only $+1$, 0, $-\frac{1}{4}$, and the limited "size of the sample" make the results quite uncertain. Each of these curves has been plotted in terms of the standard score, $y=[s-(1/m)\Sigma s]/\sigma_s$, of the data going into that particular curve. Hence only the forms of the curves are comparable. I do believe, however, that certain conclusions can fairly be accepted tentatively at least until more data are obtained. The last few questions do show a false difficulty due to their positions in the test.

I have been told that the editors arrange the subject matter of the tests so as to follow roughly the conventional treatment of the courses. The latter parts of the courses are then more difficult (as they probably should be) or are more poorly taught (as they shouldn't be). I attempted to determine whether the students did better when more of the easy or when more of the difficult questions were in the first half of their tests. The results were not at all conclusive. The students with more easy questions in the first half made better scores but the difference was so small that it could well have been caused by accidental variation.

To determine the cause of the tailing off at the end, Fig. 3 was plotted. In this I put the actual numbers of "rights," "wrongs," and "omits" for each question numbered (from the end) in the order they appeared on different students' papers. I also plotted the "last correct grade" and the "last question answered." This figure seems to show that students, instead of working at normal speed throughout the test, speed up toward the end, and answer only those questions about which they think they know the answer and those which do not require any calculation. Very few students had more than two or three "omits" at the ends of their papers. This indicates that only a very few students did not have time to read most of the questions.

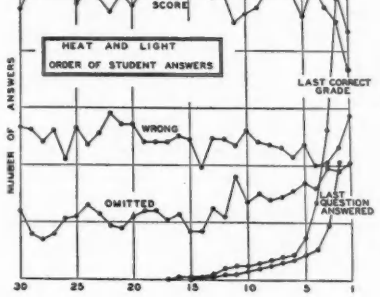

FIG. 3.

While a further study of this sort would doubtless reveal more conclusive results, these data do seem to show that the grade on a question is independent of the position of the question in the test except for the last half dozen questions. I wonder whether similar data from other colleges would show the same general results. Much more data than I have would be needed to determine quantitatively how much the grades of the last few questions must be adjusted to make them strictly comparable with the grades of earlier questions.

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"Pressure Energy"—1938

In a previous paper,[1] the writer has pointed out, as E. H. Kennard had done nine years before, that the many elementary textbooks which derive Bernoulli's equation by use of the "pressure energy" idea contain two compensating fallacies. The one consists in attributing to a liquid an energy density numerically equal to the pressure (the "pressure energy"), in addition to the densities of gravitational and kinetic energy. The other consists in ascribing constant total energy to a chosen portion of liquid as it passes down a flow tube; that is, in assuming that no work is done on the chosen portion by the surrounding liquid. Viscosity is, of course, neglected. It was suggested by the present author that there be used, instead, an alternative type of derivation in which the work done on the selected

portion by the surrounding liquid is recognized and explicitly taken into account.[2]

Of the seventeen textbooks previously cited in this connection, three[3] have appeared in new editions wherein the passages criticized have been replaced by unobjectionable material. On the other hand, three others[4] have reappeared without essential change in this respect. Five new books[5] contain "pressure energy" treatments, and two of the "Cooperative Tests for College Students"[6] included one question each based on the concept of "pressure energy." Additional discussion thus seems to be necessary if this type of treatment is to be discarded from the literature.

Private correspondence and conversation have revealed two extreme positions, one or the other of which seems to be taken by the great majority of physics teachers. Either, one is not very familiar with the idea of "pressure energy," not having written or lectured about it, and agrees that the idea is untenable, but is inclined to ask, "Why belabor the obvious?" or he *has* written or lectured about it, and is disposed to assume that any arguments advanced against it must be faulty, even if he may lack the time or the inclination to discover the presumed faults. This group seem to take about the same attitude toward the objections as we all do toward designs for perpetual motion machines, having accepted the idea so thoroughly and so intuitively that no ordinary amount of argument will suffice to dissuade them.

In seeking a better understanding of this attitude, the writer has attempted to see how good a case could be made *for* the "pressure energy" concept, and to determine precisely where this case breaks down. In doing so, he has arrived at a less extreme position, and one which he hopes will be more effective. The case for the concept appears to be as follows:

> The pressure bears the same relation to the force exerted on a particular unit volume of the liquid by the surrounding liquid as does the gravitational potential to the gravitational force per unit mass.[7] That is, the net force per unit volume due to the pressure of the surrounding liquid equals the negative space derivative of the pressure itself, just as the gravitational force per unit mass equals the negative space derivative of the gravitational potential. Thus, upon integrating along a streamline between two points, we find that the work done on unit volume by the surrounding liquid equals the decrease in pressure, just as the work done on unit mass by the gravitational force equals the decrease in the gravitational potential. Why, then, may we not treat pressure just like gravitational potential, speak of "pressure energy" as we speak of gravitational potential energy, and apply the conservation principle to the sum of these two and the kinetic energy?

The answer is that we *may* apply the conservation principle to a sum of quantities that includes "pressure energy" (provided, of course, that we otherwise ignore the work effects of the neighboring liquid), *but only so long as we deal with cases of steady flow*, for only then will the pressure be a function of coordinates alone and not of the time explicitly. It is a familiar fact that ideas of potential energy, with conservation of total energy, are completely inapplicable when the forces depend explicitly on the time. In other words, one may consider the pressure to represent the work that *will have been done* on unit volume by the surrounding liquid *when* and *if* it arrives at a place of zero pressure by means of steady-state flow.

Obviously, this formulation permits the use of the "pressure energy" concept in the derivation of Bernoulli's equation, for that equation is applicable only to steady-flow situations, and it is clear why wrong results are obtained when the "pressure energy" idea is applied to nonsteady-state cases. But the objections to existing treatments are not thereby removed, for in none of them is the true state of affairs explained. The language is always such as to permit, and sometimes such as to demand, the inference that the liquid may be endowed with "pressure energy" whether in steady flow or not, and in no case is the mutual exclusiveness of consideration of "pressure energy," on the one hand, and recognition of work relations with the neighboring liquid, on the other, explained. The following quotations furnish fairly typical examples:

> "Whenever an incompressible fluid is under a constant pressure, it possesses an ability to do work which per unit volume is called the pressure energy." [Erikson, *Elements of Mechanics.*]
>
> "The pressure intensity can be regarded as the density of a certain type of energy, the amount of which for a volume element dV is $p dV$." [H. Bateman, *Encyclopaedia Britannica*, Ed. 14, Vol. 11, p. 987.]
>
> "Moreover, even if the liquid were at rest and at zero level, each unit of volume would have the energy that would be required to pump it in against the pressure p of the liquid, and it could do an equal amount of work in forcing the liquid out." [Duff, *College Physics.*]

There is another approach to the energy aspect of the steady-flow problem, an approach which has at first seemed to some (including the present writer) to embody the idea of "pressure energy" density, but which actually does not. This is to be found in P. W. Bridgman's *The Thermodynamics of Electrical Phenomena in Metals*,[8] where we read on p. 31: "A liquid in which there is a pressure p convects energy in amount pv with it when moving across a surface." It is not intended by Bridgman that the energy *convected with* the liquid shall be thought of as *resident in* it, even though this inference seems almost fatally attractive, for he has said in a letter to the writer:

> "I heartily agree with you that one must not say that the pv-energy of a liquid 'resides in the volume of the liquid.' It is, of course, absurd to maintain that by applying a pressure p to an incompressible liquid one has thereby imparted any energy at all to the liquid. The meaning to be ascribed to pv-energy you will find

stated on page 31 of my book: 'A liquid in which there is a pressure p convects energy in amount pv with it when moving across a surface.' To my mind this is a complete statement of the meaning of pv-energy—there is no implication that the source of the energy which flows across a fixed surface when liquid also flows, is in the liquid itself. In fact, the source of the convected energy which flows across a partition A, in my Fig. 5, is obviously the work done by the external pressure p_1 and is not in the liquid itself.

"This flow of energy is merely a special case of the energy flow which always accompanies the motion of matter under stress and is discussed in the more advanced treatises on elasticity. In particular, if the moving body is under tension, as in a belt from one machine to another, the flow of energy is in the opposite direction from the motion of the belt; it would obviously be absurd in this case to think of the origin of the convected energy as being in the belt itself."

It is hoped that future textbooks will not present the "pressure energy" idea in its usual misleading form. Since the idea has for its chief virtue a slight abbreviation of treatment—an abbreviation which would be more than offset by the explanation necessary to a clear understanding of the matter—this would perhaps mean its complete disappearance.

G. A. Van Lear, Jr.

University of Oklahoma,
Norman, Oklahoma.

[1] G. A. Van Lear, Jr., Am. Phys. Teacher 4, 99 (1934).
[2] This suggested derivation is essentially that given by Lamb, *Hydrodynamics* (Cambridge, 1924), p. 19, and used in the elementary textbook edited by Duff. Lamb says of his derivation, "This is really a reversion to the methods of Daniel Bernoulli, *Hydrodynamica*, Argentorati, 1738."
[3] Miller, Spinney, and Kimball-Wold.
[4] Duff, Erikson, and Knowlton.
[5] Hausmann and Slack, Culver, Hobbie, Eldridge, and Williams. However, Professor Hobbie has informed the writer that his treatment will be changed in the next printing of his book.
[6] Forms Mechanics 1935 *B* and Mechanics 1937 *A*.
[7] Of course, any potential function could be used for the analogy; the case of gravitation is used because of its simplicity.
[8] (Macmillan, 1934).

An Annotated List of Books for the Secondary School Physics Library

MANY requests have been received by *The American Physics Teacher* for a list of books recommended as most suitable for the physics library of a secondary school. Since a list of this kind, if it were carefully compiled and annotated, bears promise of being used widely and might serve to increase interest in improving the quality and usefulness of school science libraries, the journal has undertaken its compilation and publication. Reprints will be made available at cost to all teachers of physics.

To provide a basis for making the final selection, a preliminary list has been prepared in mimeographed form by a committee consisting of Jessie A. Rodman, H. W. Le Sourd, C. R. Fountain, and the Editor. Every secondary school and college teacher who is willing to assist in this project is urged to write for a copy of this preliminary list. If the final list is to be most useful and dependable, it must represent the collective opinion of a large number of experienced teachers.

Appointment Service

REPRESENTATIVES of departments or of institutions having vacancies are urged to write to the Editor, Columbia University, for additional information concerning the physicists whose announcements appear here or in previous issues. *The existence of a vacancy will not be divulged to anyone without the permission of the institution concerned.*

23. M.S., B.S. Louisiana State Univ. Age 24, unmarried. 2 yrs teaching fellow, physics; 2 yrs practical engineering experience; 2 summers, seismic prospectings. Desires teaching or industrial laboratory position.

24. Ph.D. Age 32, married, no children. Experience: 4 yrs secondary school; 4 yrs instructor, state university; 3 yrs head of physics and mathematics, liberal arts college. Author, laboratory manual. Two research grants. Desires position in larger college or university.

25. Ph.D. Yale. Age 33, married, 2 children. Industrial research experience; 3 yrs instructor in small college. Interested in teaching in coeducational or mens liberal arts college.

26. Ph.D., with long experience in an American college in China, wishes a college teaching position.

27. Ph.D., physics, Northwestern '35. A.B., engineering, Harvard. Age 42, married, 3 children. Experience: 1 yr, lt., artillery; 12 yrs business and sales; 5 yrs college teaching. Interested in undergraduat teaching, including astronomy.

28. B.S. in E.E., M.S., physics, Dr. Phil. Nat. from German univ. (Exchange fellow from U. S.) Age 32, 7 yrs teaching experience in advanced courses and physics for engineers.

29. Ph.D., Northwestern; M.S., Pittsburgh; A.B., Muskingum. Age 34, married, 1 child. Has had 13 yrs teaching experience in two universities. Interested in teaching and research.

30. Ph.D., Univ. of Chicago. Many years experience as head of department of physics in prominent college. Author of books on physics and history of science. Large work on history of physics in preparation. Interested in college or university teaching.

Departments having vacancies or industrial concerns needing the services of a physicist are invited to publish announcements of their wants; there is no charge for this service.

Any member of the American Association of Physics Teachers may register for this Appointment Service and have a "Position Wanted" announcement published without charge.

RECENT PUBLICATIONS AND TEACHING AIDS

Intermediate and Advanced Textbooks and References

Low Temperature Physics. M. and B. Ruhemann, Physico-Technical Institute, Kharkhov, U.S.S.R. 322 p., 113 fig., 26 tables. *Cambridge Univ. Press* and *Macmillan*, $5. The authors of this survey have tried to meet the needs of physicists who are not specialists in low temperature physics and of students who have not yet selected a field of specialization. The treatment is divided into four parts: phase equilibrium; the solid state; orbit and spin; and the "free" electron. Emphasis is placed on those aspects of low temperature research that have not yet been treated in connected form in other books on physics; for example, crystal structures stable at low temperatures, and the practical aspects of gas liquefaction and rectification. The bibliography is comprehensive. The omission of an index is unfortunate.

Electrical Measurements. Harvey L. Curtis, Principal Physicist, U. S. Bureau of Standards. 316 p., 66 fig., 14 tables, 15×23 cm. *McGraw-Hill*, $4. Comprehensive descriptions of the important methods for precise comparisons of standards and absolute measurements of electrical units are provided in this text. For most of the methods every feature is discussed that will introduce an error of 1 part in 10^6 in the final result, this being the accuracy considered by the author to be the goal in most present-day electrical measurements. The main subjects treated are: definitions and principles; history of units; types of standards; international units; fundamental and derived mechanical units; construction of standards; methods of comparing standards; measurements involving two or more quantities; computation of circuit induction from dimensions; absolute measurements; and the ratio *c*.

Electron and Nuclear Physics. J. Barton Hoag, Assistant Professor of Physics, University of Chicago. Ed. 2. 511 p., 259 fig., 26 tables, 13×21 cm. *Van Nostrand*, $4. Appearing originally in 1929 under the title *Electron Physics*, this text for the upper-division or early graduate level has now been expanded to include the domain of nuclear physics as well as to modernize the original treatment of electron physics. The underlying purpose of the text is to present the experimental evidence for the important concepts of these fields. There are groups of chapters on electron properties and emission, on electrical phenomena peculiar to the outer parts of the atom, on such nuclear phenomena as positive rays, natural and artificial radioactivity, and transmutations, and on a variety of modern experimental technics. Also included are detailed directions for 39 experiments that employ apparatus simplified from the original research forms; many of these experiments, in their modified forms, are original and hitherto unpublished.

Heat and Thermodynamics. Mark W. Zemansky, Associate Professor of Physics, College of the City of New York. 400 p., 101 fig., 59 tables, 15×23 cm. *McGraw-Hill*, $4. This intermediate text on heat and thermodynamics is intended for students of physics, theoretical chemistry, and engineering who have had first calculus and the course in general college physics. The first half of the book deals with general principles—temperature, thermodynamic systems, the first law, work, heat, ideal gases, the second law, reversibility and irreversibility, the Carnot cycle, and entropy. The remainder of the book is concerned mainly with important applications to problems arising in physics, chemistry, and engineering, there being chapters on properties of pure substances, engines and refrigerators, the thermodynamics of pure substances and of special systems, change of phase, mixture of inert ideal gases, chemical thermodynamics, and ideal gas reactions. The method of approach is classical in character, and the data and illustrations are up to date. Lists of problems accompany the chapters.

General Physics Textbooks

An Outline of Physics. Albert Edward Caswell, Professor of Physics, University of Oregon. Rev. ed. 600 p., 373 fig., 1 plate, 17 tables, 14×21 cm. *Macmillan*, $3.75. Although the present edition of this text has the same general style as the 1928 edition, much of it has been rewritten to increase the clarity and directness. A number of topics have been condensed or omitted. Included in the new or expanded material are a new chapter on alternating currents, new sections on reflecting telescopes, electron diffraction, and wave mechanics, and expanded treatments of dynamos, motors, and thermionic tubes. The 504 qualitative questions and 743 graded numerical problems appear in separate lists at the ends of the chapters; answers to the odd-numbered problems are given. The text consists of six "books," three for a semester, or two for a term's work.

Survey Courses

An Orientation in Science. Members of the University of Rochester Faculty. 570 p., 281 fig., 15×23 cm. *McGraw-Hill*, $3.50. The stated objectives of this text, which is based on the orientation course in the natural sciences offered for the past ten years at the University of Rochester, is to introduce the student to the broad field of science through a presentation of the scientific method of thought and procedure, the basic principles and problems underlying the various fields of science, and the relationships between these fields. More than half the book is devoted to the physical sciences, including mathematics and geology. The discussion of scientific methods is confined to two special chapters. The 56-page chapter on "Physics," which was prepared by Professor T. R. Wilkins, is devoted almost

exclusively to "the nature of matter and energy from the viewpoint of the modern physicist," the main topics discussed being Dalton's atomic theory (previously discussed more fully in the chapter on "Chemistry"), the measurement of gas molecules, the discovery of the association of atoms of matter and electricity, discharges in gases, radioactivity, the interrelation of matter and energy, the bombardment of atomic nuclei by high speed atomic projectiles, and artificial radioactivity. Much of the classical physics discussed in the book appears under the headings of other sciences. Thus, in the 63 pages of the two chapters labeled "Chemistry," there appear the main, or sole, treatments of Newton's law of gravitation, conservation of energy, kinetic theory, atmospheric pressure, and the gas laws. Most of the material on spectra appears in the 68-page chapter on "Astronomy." Units and measurements (including the uncertainty principle) are discussed under "Mathematics." Such attempts at integration of material are commendable, and in the present book seem to have been carried out quite successfully; but because of this it would have been less misleading if the names of special sciences had not been used as the sole titles of the chapters.

Books for Secondary Schools

The Teaching of Physical Science in the Secondary Schools of the United States, France, and Soviet Russia. Alexander Efron. 303 p., 15×23 cm. *Teachers College, Columbia University*, $2.35. This study of secondary school physical science instruction here and abroad—the latter based on resident study in France and Russia—provides descriptions and comparisons of instructional methods, and discusses the implications of foreign practice for teaching in this country. Information is included on curriculums, tests, teacher training, laboratory work, equipment, and the like. The bibliography is extensive.

Radio—A Study of First Principles. Elmer E. Burns, Instructor in Physics, Austin High School, Chicago. Ed. 3. 309 p., 236 fig., 13×20 cm. *Van Nostrand*, $2. A textbook for schools and night classes on the principles of electricity as applied in radio. The main subjects dealt with are: simple receiving circuits, batteries, magnetic action of a current, Ohm's law, electron tubes, alternating currents, detectors and amplifiers, oscillating and transmitting circuits, photoelectric cells, television, and radio measurements. Simple exercises and questions are included with each chapter. In the present edition, obsolete material has been deleted and new developments added.

Lecture-Demonstrations

Demonstration Experiments in Physics. Edited by Richard Manliffe Sutton, Associate Professor of Physics, Haverford College. 553 p., 408 fig., 15×23 cm. *McGraw-Hill*, $4.50. Some four years ago the American Association of Physics Teachers adopted the idea of compiling a book on lecture table demonstrations as a cooperative undertaking. Professor Sutton and a group of collaborators were appointed as the editorial staff. Since that time this staff has been at work on the project, developing and writing the descriptions of experiments and ideas contributed by more than 200 physicists. Represented in the undertaking are 130 institutions, in nearly every state in the Union, and in Canada, England, Syria, China, and Esthonia. The result is a comprehensive, clearly written, well-organized, and beautifully printed contribution to the improvement of physics instruction. This has been a significant undertaking because of its cooperative character; even the royalties from the sale of the book will accrue to the Association as a whole and not to any individual.

Some 1200 experiments are described, and they run the gamut of physical phenomena usually covered in college and secondary school general physics courses. The experiments range from the simplest kinds, involving the most primitive apparatus, to those that will tax the facilities of a well-equipped laboratory. Because many colleges and schools do not possess the facilities of a large university department, a large number of the experiments have been made simple; probably half of them involve apparatus that is within the range of the average secondary school. The editors clearly have not attempted to collect 1200 new experiments, but have followed the more useful course of presenting a good cross section of the art of demonstration as it is practiced by physics teachers today; nevertheless, it is safe to say that even the most experienced of demonstrators will find in the book many experiments that are new to him.

The book opens with an excellent chapter on general principles, methods, and tools of demonstrations. The experiments proper appear in six main sections—mechanics, wave motion and sound, heat, electricity and magnetism, light, atomic and electron physics—each of these sections has a number of subdivisions, and each experiment in the latter is given a title. This arrangement, together with a very complete index, enables one to find material on any detailed topic in the shortest possible time. More than usual emphasis is placed on atomic and electronic physics, there being 121 experiments on these fields, which are newest, and for which the literature on demonstrations consequently has been most meager. At the end of the book there is a list of all contributors and a bibliography. Not only will the book be of immediate use to all teachers who possess it, but it will doubtless stimulate a wider and greater interest in the art of demonstration and in the designing of interesting, new experiments.

The editors who collaborated with Professor Sutton are: F. L. Brown, University of Virginia; L. E. Dodd, University of California at Los Angeles; L. A. DuBridge, University of Rochester; J. D. Elder, Haverford College; G. P. Harnwell, University of Pennsylvania; C. W. Heaps, Rice Institute; R. M. Holmes, University of Vermont; L. R. Ingersoll, University of Wisconsin; N. C. Little, Bowdoin College; P. M. Morse, Massachusetts Institute of Technology; L. W. Taylor, Oberlin College; M. R. Wehr, Drexel Institute of Technology.

Miscellaneous Books

Both Sides of the Microphone: Training for the Radio. John S. Hayes, Assistant Production Chief, Mutual Network, and Horace J. Gardner, radio commentator. 180 p., 12×19 cm. *Lippincott*, $1.25. A simple, nontechnical

account for the radio listener and for those who desire vocational information concerning the sales, program, engineering, and other aspects of radio work.

Scientific German for Science and Premedical Students. Edited by CURTIS C. D. VAIL, University of Buffalo. 248 p., 29 fig., 13×20 cm. *Crofts*, $1.80. Well rounded out readings are provided, about half of them being in physics, chemistry, and geology. The physics readings occupy 28 pages and consist of extracts on mechanics taken from Volume 33 of the *Mentor Repetotorien*. A 75-page vocabulary is included.

Astronomy. ROBERT H. BAKER, Professor of Astronomy, University of Illinois. Ed. 3. 537 p., 288 fig., 22 tables, 6 maps, 15×23 cm. *Van Nostrand*, $3.75. The present edition of this successful textbook for college and university students takes into account advances in the field since the appearance of the second edition in 1923, and has otherwise been revised to improve its value as a text and reference. A new feature is the lists of questions at the ends of the chapters. The star maps have been improved, new photographs added, and the account of the galactic system modernized. This text should not be confused with the author's *An Introduction to Astronomy* (1935), which is intended for a still more elementary course.

Synoptic and Aeronautical Meteorology. HORACE ROBERT BYERS, Air-Mass Analysis Section, U. S. Weather Bureau. 288 p., 63 fig., 17 tables, 6 maps, 15×23 cm. *McGraw-Hill*, $3.50. Air-mass analysis, one of the most important developments in meteorology in recent years, is covered in all its practical aspects in this text for airplane pilots and students of meteorology. The theoretical basis of air-mass analysis is discussed and numerous examples are then given of its application to the weather map and forecasting. Chapters are also included on condensation and precipitation, fog, storms, aircraft icing, atmospheric turbulence, and dust storms. The book was prepared under the auspices of Transcontinental and Western Air, Inc.

Electron Optics in Television. I. G. MALOFF AND D. W. EPSTEIN, Research Division, RCA Manufacturing Co. 310 p., 197 fig., 16 tables, 15×23 cm. *McGraw-Hill*, $3.50. This technical treatment of electron optics and television cathode-ray tubes begins with a brief description, intended for the nonspecialist, of the cathode-ray television system. The next part discusses the theory of electron emission and electron optics, with emphasis on pure electrostatic lenses involving two coaxial cylindrical electrodes. The last part, constituting about half of the book, deals with the problems encountered in designing practical tubes and associated apparatus for producing satisfactory television pictures. Emphasis is placed on those aspects of the subject with which the authors have had first-hand experience at the RCA laboratories.

Engineering Electronics. DONALD G. FINK, Managing Editor, *Electronics*. 371 p., 217 fig., 11 tables, 15×23 cm. *McGraw-Hill*, $3.50. This text on applied electronics was developed from material collected originally for a lecture course given to engineers of the Westinghouse Lamp Company who had a good foundation in electricity but no special training in electronic concepts and methods. From the experience with these lectures the author concluded that a practical background in electronic technology should include an understanding of the possibilities and limitations of electronic conduction, a familiarity with different types of tubes and their special fields of use, and a knowledge of circuits in which the tubes are employed; and it is along these three lines that he has developed the present treatment. Practically no calculus is used in the book. Each chapter includes a list of problems and a bibliography.

Preparation of Scientific and Technical Papers. SAM F. TRELEASE, Professor of Botany, Columbia University, and EMMA SAREPTA YULE, Head of the English Department, College of Agriculture of the University of the Philippines. Ed. 3. 125 p., 1 fig., 10 tables, 12×18 cm. *Williams & Wilkins*, $1.50. Designed to provide practical and specific information on effective procedures and matters of style in the preparation of papers and theses, this manual represents a thorough revision of a pamphlet first issued many years ago to aid students in writing themes and theses at the College of Agriculture, University of the Philippines. Rules of grammar and rhetoric are not included, since they are already available in many handbooks. Some of the rules and practices recommended differ from those followed in physical literature, and some rules and information peculiar to physics are missing; indeed it would be almost impossible at the present time to prepare a single, compact manual that takes account of all the variations in usage and style to be found in the literatures of the various sciences. Yet the present manual contains much useful information and advice which, if taken to heart by inexperienced authors, would serve to improve materially the quality of scientific papers and, incidentally, lessen the tasks of those who have to edit them.

CHARTS

Graphic Story of Light Output. 3 p., 1 fig., 21×27 cm. *Westinghouse Electric and Manufacturing Co.* (Technical Press Service, East Pittsburgh, Pa.), gratis. A graph, and accompanying explanation, which shows that 4 major improvements made in the 60-w Mazda lamp during the past 10 years have increased the initial light output from 666 to 828 lumens.

MOTION PICTURE FILMS

Aluminum: Mine to Metal. 16 or 35 mm, silent, 30 min. *Bureau of Mines Experiment Station* (4800 Forbes St., Pittsburgh), lent gratis. Produced by the Aluminum Company of America, this film shows the industrial uses of aluminum, the production and treatment of bauxite to form the metal, and the production of aluminum by electrolysis.

PAMPHLETS

New Wallace Replica Diffraction Gratings. Strip folder No. 19. 8 p., 9×19 cm. *Central Scientific Co.*, gratis. Contains a brief discussion of the history and principles of diffraction gratings, and their importance for demonstrations and experiments.

The Last Word in Telephotography. JOHN MILLS. 12 p., 4 fig., 15×23 cm. *Bell Telephone Laboratories* (463 West St., New York), gratis. An outline of fundamental operations of the art of electrical communication, using as an example the newly developed system for transmitting pictures.

Available Graduate Appointments and Facilities for Advanced Study in Physics 1939–1940

This survey of opportunities for advanced study in physics for the academic year 1939–1940 is based on information obtained from a questionary sent to all departments of physics in the United States and Canada known to offer graduate work. The information must be interpreted as estimates rather than exact descriptions of the conditions that will prevail in these departments next year. The Editor wishes to express his appreciation of the cooperation of the staff members of the departments listed, without which the information could not, of course, be assembled.

Few appointments are available compared with the probable number of candidates and the mere publication of the list obviously does not improve this situation. The purpose of the information is to enable the student to choose intelligently the institutions in which he desires and can afford to study, and hence to render it unnecessary for him to send out applications promiscuously or to depend entirely on information obtained casually or through connections of a personal nature. If the list is used judiciously by students and their advisers, its publication will tend to prevent rather than encourage an unnecessarily large number of applications. *The student, with the help of his adviser, should select a small number of institutions in which he feels best qualified by his interests and abilities to study, and in any one of which he would be willing to accept an appointment as soon as it is offered. When he accepts an appointment, other pending applications should be withdrawn immediately.*

Unless otherwise specified, the application must be filed with the person designated *before March 1;* if no person is designated, address the head of the Department of Physics. "M only" means that the master's degree is the highest degree granted. "No form" means that a special application form is neither furnished nor required. The numerals preceding the parentheses indicate the probable number of vacancies for next year; those in parentheses indicate the total number of appointments existing in the department; e.g., 2(3) *fellows* means that three fellowships exist, two of which probably will be vacant and open to competition next year. Except where otherwise indicated, appointees do not have to pay tuition (t.) or fees (f.). Under *R* are listed fields of research that are stressed in the department and under *U*, unusual facilities for research and study.

A. and M. College of Texas, Dean T. D. Brooks, College Station, Tex. M only. 0(4) *graduate assistants*, lab. teach., $405. Residents of state pay $50 t.; others, the nonresident t. of their state univ. *R:* spectroscopy; x-ray diffraction; polarimetry.

Boston College, Chestnut Hill, Mass. June 1; M only; no form. 3(6) *graduate assistants*, 8 hr/wk general lab., $300. Appointees must have had 2 yrs advanced physics, advanced calculus, and differential equations. *R:* electronics; electromagnetic waves. *U:* electronics.

Boston University, Dean H. M. LeSourd, 84 Exeter St., Boston, Mass. Apply any time, 1(1) *fellow*, $600 and tuition; 3(3) *assistants*, tuition, 3(3) *scholars*, $200 less t. All appointees pay about $15 f.; service consists of lab. asst., etc. *R:* spectroscopy; many fields in mathematical physics. *U:* 30-ft Littrow spectrograph, Lummer-Gehrcke plates, echelons, étalons.

Brown University, Registrar of Graduate School, Providence, R. I. 1–2(1–2) *scholars*, study and research, t. and f. remitted; 2(6) *graduate assistants*, 18–20 hr/wk lab. teach., $500 first year; 2(3) *minor assistants*, 6 hr/wk service, t. and f. remitted; 1–2(1–2) *fellows*, study and research, $500 less $60 f./course, unless remitted by summer research or other service. *R:* properties of single metal crystals (electron diffraction, photoelectricity, contact potentials, conductivity, magnetic susceptibility); theoretical and experimental acoustics, including supersonics; atomic theory calculations (e.g., atomic wave functions); foundations of physics. *U:* Single metal crystal technic; electroacoustics.

Bryn Mawr College, Dean Eunice M. Schenck, Bryn Mawr, Pa. 2(3) *half-time demonstrators*, lab. teach. and asst., $750; 1(1) *fellow*, 3 hr/wk service, $860 less $320 t.; 1(1) *scholar*, no service, $400 less $320 t. *R:* properties of metals, particularly surface properties; x-ray crystal structure; biophysics.

California Institute of Technology, Graduate Dean, Pasadena, Calif. Feb. 15. 10(25) *graduate assistants*, lab. and lec. teach., room, board, t. and f. *U:* nuclear physics; cosmic rays; spectroscopy; physics of solids; x-rays; ultra-short radio; low temperatures; geophysics; biophysics; isotopes.

Case School of Applied Science, Prof. D. C. Miller, Cleveland, O. M only. 0(2) *graduate assistants*, lab. and lec. asst., $600. *R:* acoustics; electron diffraction; ultraviolet spectroscopy; x-ray diffraction; meteorology. *U:* acoustics.

Central Scientific Company. Dr. M. N. States, Chicago, Ill. Apr. 1; no degree awarded. 2(2) *industrial fellows*, development lab., factory inspection, etc., $1200 for 12 mo., less deductions for social security, etc.

Charles A. Coffin Foundation. The Secretary, Schenectady, N. Y. Jan. 15. *Charles A. Coffin fellowships* for research in physics, applied electricity, and physical chemistry either here or abroad; or some portion or all of the fund may be used to further research at any institution in this country.

Colorado College, Prof. P. E. Boucher, Colorado Springs, Colo. May 1; M only. 1(1) *graduate teaching fellow*, 6–10 hr/wk lab. asst., remission of $225 t. *R:* x-rays; high frequency measurements; optics; photography.

Columbia University, New York, N. Y. 5(15) *assistants*, lab. and other teach., $1000 less $20 f.; 3(4) *part-time assistants*, lab. asst., grading, $200 to $500 less course fees; 2(2) *fellows*, study and research, $100 to $15000 less $400 (or less) t.; 2(2–4) *scholars*, $400 to $500 less $400 t. For assistantships apply by letter before Mar. 1, and for part-time assistantship before July 1, to Prof. George B. Pegram; for fellowships and scholarships, obtain form from The Secretary of the University. *U:* molecular beams; magnetism; properties of solids; nuclear physics; x-rays.

Cornell University, Prof. R. C. Gibbs, Ithaca, N. Y. Jan. 20 to Feb. 10. 4–6(22) *graduate assistants*, lab. asst., $600 less $37 f.

Dartmouth College, Prof. Norman E. Gilbert, Hanover, N. H. Apply any time; M only; no form. 2(5) *graduate assistants*, half-time lab. and lec. asst., $800.

De Pauw University, Prof. Orrin H. Smith, Greencastle, Ind. M only; Aug. 1; no form. 0(1) *graduate assistant*, lab. asst., $200 or more. *R:* x-rays; ionization in gases.

Duke University, Dean Calvin Hoover, Durham, N. C. 1(2) *fellow*, $600 to $700 less $281 t. and f.; 2–3(5) *graduate*

assistants, $500 to $550 less $241 t. and f.; 1(2) *scholar*, $400 less $281 t. and f. Services for all appointments consist of lab. asst. and grading. *U:* atomic and nuclear physics; magnetism; spectroscopy.

Emory University, Prof. W. S. Nelms, Emory Univ., Ga. Apr. 15, M only; no form. 1(1) *graduate assistant*, general asst., $225 to $500, less $225 t.; several *university scholars*, t. of $225 remitted.

Indiana University, Prof. Allan C. G. Mitchell, Bloomington, Ind. 3–5(6–7) *graduate assistants*, 8 hr/wk teach., $500 to $700. *R:* nuclear physics; theoretical physics. *U:* 200-mg radium neutron source; cyclotron under construction.

Institute of Paper Chemistry (affiliated with Lawrence College), Dean, Appleton, Wis. May 1. 10–15 *scholars*, service arranged, board, room, remission of t. and f. Besides physics, the applicant's undergraduate preparation must include 4 yrs chemistry, 2 yrs mathematics, and a ready knowledge of German. *R:* applied optics; mechanics; hydraulics; photoelectricity. *U:* color measurements; optical characteristics of paper; applied photoelectricity.

Iowa State College, Graduate College, Ames, Ia. 1(1) *graduate assistant*, class and lab. asst., $540; 3(6) *teaching fellows*, lab. asst., $450; 1(1) *teaching scholar*, lab. asst. $225. All appointees pay $12 f./quarter. *R:* applied physics. *U:* electronics; physics of crystals; cathode rays; biophysics; physics of soils; photography; illumination.

Louisiana State University. Prof. D. V. Guthrie, University, La. M only. 5(11) *graduate fellows*, lab. teach., $450 less $60 t. and f. *R:* x-rays; electronics; spectroscopy.

Massachusetts Institute of Technology, Cambridge, Mass. 4–6(18) *teaching fellows*, teach. or lab. asst., $600 to $800 and t.; several *tuition scholars*, study and research, t. and f. of $600 remitted; several *half-tuition scholars*, study and research, half of t. and f. of $600 remitted. For fellowship, apply by letter to Prof. J. C. Slater; for scholarships, apply on form to Dean H. M. Goodwin. *U:* spectroscopy; electronics; x-ray crystal structure; high voltage, nuclear structure, and radioactivity; applied optics; classical and modern theoretical physics.

Mount Holyoke College, South Hadley, Mass. M only; Mar. 1 or possibly later. 2(1 ordinarily) *fellows*, study, apply on form, $600 and remission of t. and f.; 1(1) *graduate assistant*, 10 hr/wk general asst., apply by letter, t. and f. remitted. *R:* effect of stress on electrical resistance; discharge through gases; Raman effect; soft x-rays.

New York University, Washington Square College, Prof. C. W. Van Der Merwe, New York, N. Y. March 31. 2(3) *graduate assistants*, $1000; 0(4) *instructors*, $1800. Appointees pay $3 to $6 f.; teach 12 hr/wk. *R:* theoretical and experimental nuclear physics; band, infra-red and hyperfine spectroscopy.

Ohio State University, Columbus, O. 10(22) *graduate assistants*, lab. teach., $450; 1(1) *assistant*, research asst., $990; 1–2 (varies) *fellows*, study and research, $400; 1–2 (varies) *scholars*, study and research, $250. For all assistantships apply by letter to department chairman; for other appointments apply on form to graduate dean. *R:* nuclear physics; infra-red spectroscopy; band spectra; x-rays and crystal structure; theoretical physics; Zeeman effect. *U:* nuclear physics; infra-red spectroscopy; Zeeman effect.

Oregon State College, Prof. W. Weniger, Corvallis, Ore. Apr. 1. 1–2(4) *graduate assistants*, teach. and lab. asst., $540 less $25/term t. and f. 0(1) *fellow*.

Polytechnic Institute of Brooklyn, Prof. Erich Hausmann, Brooklyn, N. Y. Apr. 1; M only (Ph.D. in chem. and elec. eng.); no form. 1(2) *graduate fellow*, grading, stipend undetermined. *R:* optics; electricity; mathematical physics. *U:* spectroscopy; field emission; electrical conduction.

Princeton University, Dean of Graduate School, Princeton, N. J. (1–2) *Proctor fellows* (rarely awarded to a first-year student), $1400; (2–4) *fellows*, $700; (1–2) *junior fellows*, $400; (6–8) *research assistants*, $600. Fellows devote time to study and research; assistants give half-time help to some member of staff. All appointees pay $5 f. *R:* line spectra; infra-red spectra; ionization in gases; mass spectrography; nuclear physics; quantum mechanics and its applications to atomic and molecular problems. *U:* spectroscopy; high voltage; mass spectrographs; cyclotron.

Purdue University, Prof. K. Lark-Horovitz, Lafayette, Ind. May 15. 2(6) *quarter-time assistants*, 6 hr/wk lab. asst., candidate must take comprehensive exam. on B.S. level, $350 less $8 f.; 2(10) *half-time assistants*, 9 hr/wk class and lab. asst., candidate must take comprehensive exam. on M.S. level, $700 less $8 f.; 2(7) *instructors*, 9 hr/wk teach., candidate must have Ph.D., $1400 up. *R:* x-rays; electron diffraction; nuclear physics; acoustics; spectroscopy.

Rutgers University, New Brunswick, N. J. Apply any time. 2(4) *graduate assistants*, half-time lab. asst., $600; 2 (varies) *graduate scholars*, t. and f. remitted.

Smith College, Northampton, Mass. Ordinarily M only. 1 *teaching fellow*, lab. and lec. asst., apply by letter to Prof. A. T. Jones, $600; 1 *fellow*, study and research, apply on form to Dean Marjorie H. Nicolson, stipend consists of board and room. *R:* sound; electronics; photography; ultraviolet spectroscopy; spectrophotometry.

Stanford University, Prof. D. L. Webster, Stanford University, Calif. May 1; no form. 1(6) *teaching assistant*, lab. teach., $700 less $115/quarter or $7/unit t. *R:* x-rays; atmospheric electricity; nuclear research; theoretical physics; ultra-short radio waves.

Syracuse University, Syracuse, N. Y. M only. 3(6) *graduate assistants*, 12 hr/wk lab. teach., apply to Prof. R. A. Porter, $600; 1(1) *scholar*, 4 hr/wk service, apply to Dean W. L. Bray, t. remitted. All appointees pay $5 f. *R:* thermal conduction and expansion; magnetism; electrical conduction in gases; spectroscopy.

University of California at Los Angeles, Prof. Joseph Kaplan, Los Angeles, Calif. 1(4) *teaching assistant*, lab. teach., $650, apply before May 1; ?(5) *readers*, grading, $25 to $100, apply before Sept. 1. All appointees pay $46 f.; nonresidents also pay $150 t. unless exempted on basis of high scholarship. *R:* acoustics; spectroscopy; thermionics. *U:* infra-red spectroscopy; acoustics; molecular spectra.

University of California, Berkeley, Calif. 10–15(29) *teaching assistants*, lab. asst., grading, etc., $650; various *graduate fellows*, $300 to $1200. All appointees pay $52 f.; nonresident t. of $150 usually remitted. Applicants not already in residence should apply for assistantships. *U:* spectroscopy; nuclear physics; mobility of ions; mathematical physics.

University of Chicago, Committee on Fellowships and Scholarships, Chicago, Ill. 3(6) *graduate assistants*, teach. and lab. asst., $750 less $33.33 f./course; 5(5) *fellows*, lab. asst., grading, etc., $500 less $300 t. and f.; 5(5) *graduate service scholars*, lab. asst., library work, etc., remission of $300 t. and f.

University of Cincinnati, Graduate Dean, Cincinnati, O. Mar. 15. 1(1) *graduate assistant*, lab. asst., $400; 5–6(5–6) *fellows*, study and research, $300 to $500; several *scholars*, study and research, remission of various f. All appointees pay $5 f. *R:* spectroscopy; soft x-rays; atmospheric electricity. *U:* soft x-rays, etc.

University of Illinois, Urbana, Ill. 1–3 *graduate assistants*, half-time teach., $700; *scholars* and *fellows*, study and research, $300 to $600. New students pay $10 f. For assistantships apply between Jan. 1 and Mar. 1 to Prof. F. W. Loomis; for other appointments apply before Feb. 15 to Dean R. D. Carmichael. *R:* spectroscopy (band and line spectra, hyperfine structure); nuclear physics; mass spectra; acoustics; theoretical physics; fluorescence; electron optics. *U:* spectroscopy (vacuum, visible, near infra-red); nuclear physics (cyclotron, linear accelerator, Ra-Be source); acoustics; fluorescence; theoretical physics.

University of Iowa, Prof. G. W. Stewart, Iowa City, Ia. Several *graduate assistants*, *scholars*, *fellows*, *research*

assistants, and *research associates*. *R:* spectroscopy; resonance radiation; molecular beams; single crystals; nuclear physics; x-rays, and x-ray diffraction in liquids; electron excitation.

University of Kansas, Lawrence, Kan. ?(3–4) *graduate assistants*, 13 hr/wk class and lab. teach., $330; *university scholars* (6–7 for whole university), 0–6 hr/wk service, $250; *university fellows* (3 for whole university), 0–6 hr/wk service, $400. All appointees pay $65 and lab. f.; nonresidents pay additional $110. For assistantships, apply any time by letter to Prof. F. E. Kester; for other appointments apply on form to Dean E. B. Stouffer. *U:* dielectric constants of liquids and gases; thermal and optical properties of liquid amalgams.

University of Maine, Prof. C. E. Bennett, Orono, Me. Apply any time; M only; no form. 1(2) *graduate fellow*, lab. asst., $600.

University of Michigan, Ann Arbor, Mich. 5 (15) *teaching assistants*, lab. teach., $300 to $600; 3(1–6) *research assistants*, research asst., $100 to $1200; 2(1–3) *fellows*, study and research, $500 to $1000. All appointees pay $150 t. and f. For assistantships apply to Prof. R. A. Sawyer by Mar. 15; for fellowships, to Graduate Dean by Feb. 15. *R:* sound; spectroscopy; x-rays; electronics; vacuum tubes; radio. *U:* infra-red spectroscopy; nuclear physics; cyclotron; high potential.

University of Minnesota, Minneapolis, Minn. 5(15) *teaching fellows*, lab. teach., $600. *R:* x-rays; electronics; atomic structure; spectroscopy. *U:* nuclear physics; mass spectroscopy.

University of Missouri, Columbia, Mo. 1–2(4) *graduate assistants*, lab. teach., $500 less lab. f. and $30–60 t. and f.; *Gregory scholars* (10 for university), study and research, $300 less lab. f. and $60 t. and f. An advanced student who has begun research may be awarded a $600 fellowship for study and research. For assistantships apply by letter to Prof. H. M. Reese, usually before Apr. 1; for scholarships, apply on special form to graduate dean before Mar. 1. *R:* x-rays; biophysics; photovoltaic effect; ionizations. *U:* diffraction of x-rays in liquids; biological effects of radiation.

University of Nebraska, Prof. H. H. Marvin, Lincoln, Neb. M only. 3(6) *graduate assistants*, 6–8 hr/wk, in charge of lab. secs., $480 less $6 f. *R:* spectroscopy; x-rays; conduction of electricity in gases; electric and magnetic measurements.

University of North Carolina, Dean W. W. Pierson, Chapel Hill, N. C. Feb. 15. 1(1) *teaching fellow*, usually awarded for third or fourth graduate year, $500; 2½(3½) *graduate assistants*, $450. Total service for each appointee is 15 hr/wk lab. asst. and grading. All appointees pay $26 f. which covers laundry, infirmary, etc. *R:* infra-red spectroscopy; biophysics; interactions of electrons and gamma-rays with matter. *U:* excellent grating spectrograph for infra-red; cloud chambers; 3-million-volt Van de Graaff generator under construction.

University of Notre Dame, Secretary of Graduate School, Notre Dame, Ind. 4(10) *graduate assistants*, lab. asst., $750 less $10/semester hr t. *R:* physics of rubber; electronics; nuclear physics (interaction of high energy electrons with matter). *U:* nuclear physics (2.4 Mev Van de Graaff generator).

University of Oklahoma, Prof. H. L. Dodge, Norman, Okla. Mar. 1 if possible, but later applications accepted; 6(8) *graduate assistants*, 18 hr/wk lab. asst., $400; 1(3) *instructor* (*half-time*), teaching college physics, $800; 2(2) *research fellows and scholars*, 12 hr/wk on own research, $300; 3(4) *university scholars*, t. and f. remitted. *R:* Raman effect, molecular and crystal structure; geophysics; photoelectricity; x-ray spectroscopy; separation of isotopes. *U:* Raman effect.

University of Pennsylvania, Philadelphia, Pa. 1(2) *laboratory assistant*, half-time lab. asst., $500, apply by letter before Apr. 1 to Physics Department. For the following appointments, which are open to general competition in the graduate school and require no services, apply on form before Mar. 1 to Dean E. B. Williams: *Harrison research fellows*, $1500; *Harrison fellows*, $600; *Harrison* and *university scholars*, $200 down to t. remitted. All appointees pay minor fees. *U:* the solid state; x-ray and electron diffraction; radioactivity; nuclear physics.

University of Pittsburgh, Prof. E. Hutchisson, Pittsburgh, Pa. 2(8) *graduate assistants*, lab. teach., $500. *R:* not limited. *U:* physics of metals; optical pyrometry.

University of Rochester, Prof. L. A. DuBridge, Rochester, N. Y. 2(7) *graduate assistants*, lab. asst., $600; 1(5) *fellows*, research asst., research experience required, $600; 1(4) *graduate assistant*, Institute of Optics, teach. and research (apply to Prof. Brian O'Brien), average stipend, $600. All appointees pay $5 f. *R:* electron emission; nuclear physics; optics; biophysics. *U:* cyclotron; optics.

University of Southern California, Mrs. F. B. Watt, Los Angeles, Calif. 2(2) *fellows*, lab. asst., $500 less $240 t. and f. *R:* electrical measurements; vacuum-tube phenomena.

University of Texas, Prof. S. Leroy Brown, Austin, Tex. Sept. 1; no form. 5(15) *tutors*, in charge of lab. secs., $300 to $1000; 5(15) *graduate assistants*, lab. asst., $150 to $300. All appointees pay $50 t. and f. *R:* geophysics; electric waves; thermionics; optics; astrophysics; x-rays. *U:* thermionics; x-rays; geophysics; astrophysics.

University of Vermont, Prof. G. P. Burns, Burlington, Vt. M only; Feb. 1. 4(8 for university) *research fellows*, max. of 8 hr/wk lab. asst., $800. *U:* photoelectric, thermoelectric, and photovoltaic effects.

University of Wisconsin, Madison, Wis. Feb. 15. 2–3(7–8) *research assistants*, 20 hr/wk service, $600; 4–5(15–16) *teaching assistants*, 14 hr/wk lab. teach., $750; 0–1(1–2) *fellow*, 4 hr/wk service, $600; 3–4(4–5) *alumni research fellows* and *scholars*, study and research, $400 to $600; 0–1(0–1) *scholar*, study and research, $250. All appointees pay $54 t. and f. For assistantships apply to Prof. L. R. Ingersoll; for fellowships and scholarships, to Dean E. B. Fred. *U:* nuclear physics; electronics; spectroscopy; thermodynamics.

University of Wyoming, Laramie, Wyo. M only; no form. 1(1) *graduate assistant*, lab. and quiz asst., grading, $500 less $30 t. and f. *R:* single crystals (zinc); evaporation.

Vanderbilt University, Graduate Dean, Nashville, Tenn. M only. 1(1) *scholar*, 6 hr/wk library, $300 less $203 t. and f.; 1–2(1–2) *fellows*, 6–8 hr/wk lab. asst., $500 less $203 t. and f.

Washington University, Prof. G. E. M. Jauncey, St. Louis, Mo. 2(3) *graduate assistants*, lab. asst., $700 less $75 t. and f. *R:* photoelectricity; electron scattering; x-ray scattering; ionization of gases.

Wellesley College. Prof. Louise S. McDowell, Wellesley, Mass. M only; no form. 1(2) *assistant*, 22 hr/wk lab. asst., grading, etc., $600. *R:* dielectrics.

Wesleyan University, Department chairman, Middletown, Conn. Apply any time; M only; no form. 1(3) *half-time graduate assistant*, lab. asst., grading, etc., $600 to $800. *R:* piezoelectricity; high frequency phenomena.

Westinghouse Electric and Manufacturing Co., J. H. Belknap, Technical Employment and Training Dept., Pittsburgh, Pa. 5 *post-doctorate research fellows*, complete freedom and support of research on project proposed by applicant, the work to be carried on in Westinghouse Research Laboratories, $2400. *U:* nuclear physics; electronics; ferromagnetism; dielectrics.

Yale University, Prof. John Zeleny, New Haven, Conn. No form. 4(7) *laboratory assistants*, lab. asst., grading, $800 less $315 t. and f.; 2(2) *research assistants*, lab. asst., grading, $1200 to $1500 less $315 t. and f. *U:* magnetism; spectroscopy; radioactivity; x-rays; nuclear physics; low temperatures; theory of molecular forces.

[*This list will be continued in the February, 1939 issue.*]

DIGEST OF PERIODICAL LITERATURE

Laboratory and Shop Notes

Cellophane lantern slides. A. J. Ansley; *J. Sci. Inst.* **15**, 304, Sept., 1938. To produce printed lantern slides, remove the surface grease and moisture from a sheet of Cellophane, place the latter between a thin sheet of cardboard and a piece of carbon paper of the color desired, and insert in the typewriter. For diagrams, India ink may be employed if the Cellophane is entirely free from grease. Mount the Cellophane sheet between lantern slide cover glasses and bind.—H. N. O.

Hints on silvering glass. F. E. J. Cockenden; *J. Sci. Inst.* **15**, 206–207, June, 1938. The following well-known formula is due to Edel:

(A) *Silvering component.* Dissolve 1 oz of silver nitrate in 8 oz of distilled water. Add ammonia drop by drop until the brown precipitate first formed is redissolved. Filter, or leave for a day to settle and then decant. Add distilled water to make a total of 16 oz. Since the addition of ammonia is usually overdone, it is useful to hold back a crystal or two of the nitrate with which to effect a final "balance."

(B) *Reducing component.* Dissolve 1/40 oz of potassium sodium tartrate (Rochelle salts) in 10 oz of distilled water. Boil, add 1/180 oz of silver nitrate, and continue boiling until a heavy grey precipitate forms. Allow to cool and filter, or leave to settle and decant. The difficult measurement of 1/180 oz of silver nitrate may be solved by setting aside ¼ oz of solution (A) before ammonia is added and making thus up to a total of 5½ oz; 1 oz of this diluted solution contains 1/175 oz of silver nitrate, which is accurate enough.

Keep the two solutions in clean glass-stoppered bottles. Protect solution (A) from light. The efficiency of solution (B) is not affected by the light silver deposit which soon appears on the sides of the bottle.

Silvering process. (1) Use a parallel-sided glass or porcelain dish slightly larger than the article to be silvered. Wash the dish with soap and water, rinse with tap and distilled water, and put this dish aside containing enough distilled water to cover the article to be placed in it. (2) Similarly, cleanse the article to be silvered. Then, to insure the removal of surface grease, treat the article with undiluted nitric acid, either by immersion or by "wetting" the surface to be silvered. Do not use strong alkalis to remove grease as they have a slight etching effect on glass. Finally, rinse the article with tap and distilled water, and place it while still wet in the dish already filled with distilled water. The surface to be silvered may be placed face upwards or downwards. (3) Filter equal quantities of solutions (A) and (B), *each diluted* with an equal volume of distilled water, into separate test tubes. Boil each solution gently for several minutes and then, without shaking, cool the test tube in cold water. (4) The following procedure precludes oxidation of the silver deposit by oxygen dissolved in the solutions: pour off or remove with a syringe the water covering the article; immediately mix the contents of the test tubes, shake gently, avoiding as far as possible the absorption of air, and pour over the article in the dish until it is well covered. Cover the dish with a clean lid or filter paper and leave it for 3–4 hr. Then pour off the fluid, rinse the article in tap water, and allow it to dry. Mechanical toughness of the film is increased by leaving it untouched for 24 hr after drying. A bluish white fog in the solutions at any time indicates tap water contamination and should be avoided. —H. N. O.

Training for Industry

Training for industry. E. F. duPont; *Key Reporter* **3**, 1, Autumn, 1938. The duPont de Nemours company, which employs some 5000 college-trained people, finds that men with technical training are generally of more value to the organization, immediately and potentially, than men having merely a liberal education. Technical training fits a man for work of considerable immediate responsibility in the research, engineering, or manufacturing departments; and, with this initial experience in the fundamentals of the business, he is in a position to progress when opportunity affords. A technical training is exceedingly advantageous even for industrial occupations that are not so patently technical; for example, purchasing work and higher managerial positions. It affords a ready tool by which the perception is facilitated, whereas to the liberally trained man a complex industry is more or less of a riddle. Liberal scholarship is a desirable attainment; but it is much more feasible for the technical graduate to acquire a satisfactory measure of "culture" than for the liberal arts graduate to acquire skill in things technical.—D. R.

Democracies and the Sciences

Science and democracy. H. E. Sigerist; *Sci. & Soc.* **2**, No. 3 (1938). Although one cannot establish a simple causal relationship which will show that democratic society alone can furnish the soil suited for the development of science, yet it cannot be a mere coincidence that science actually has flourished in democratic periods. It thrived in the Greek city-democracies and, still more, in the great democratic period after the French Revolution. It is true that Greek science reached its peak in the Alexandria of the Ptolemies; that the great scientific development in the 16th to 18th centuries was by no means limited to England and Holland; that in the 19th century science was cultivated just as much in imperial Germany as in democratic France or England; that great scientists were found even in Tsarist Russia. Nevertheless, as brief historical analysis will show, the basic forces leading to the rise of democracy and of science are the same.

But first let us note that some historians still view the history of science as the free play of personalities of genius. The bio-biographical approach still dominates in most textbooks. Sometimes an attempt is made to trace the history of definite ideas or to picture the general cultural and philosophic background of a scientific period, but hardly ever is an effort made to dig deeper so as to uncover the roots of the phenomena. Nobody will deny the part played by men like Galileo, Newton, or Leibniz. History is made by human beings. But men do not live alone; they are members of societies through which they are conditioned. Potential men of genius have always existed, but the socio-economic conditions under which they live determined whether they could develop their genius and in what direction they would apply it.

Democracy, although greatly discussed by the Greeks, was a mere episode in the ancient world; the Athenian state was a democracy of the free citizen only, while the majority of the population consisted of slaves. The chief incentive to scientific research lay in the fact that the Greeks were a seafaring nation; navigation requires astronomical knowledge which in turn calls for mathematics. What is commonly called "pure" science also existed in Greece, but we should regard the distinction between "pure" and applied science as obsolete; practice always requires theory, and theory leads to practical application.

The fact that ancient economy was slave economy was a handicap to science. With labor plentiful and cheap, there was no demand for laborsaving machines. With a population consisting mainly of slaves and poor farmers, there was no demand for increased industrial production. The principle of the steam engine was recognized but never applied; the engines of Hero remained on paper as there was no economic need for them.

In the feudal world of the Middle Ages the form of production and the structure of society were almost static. Man was born into a status which determined his way of living. The tenant farmer delivered part of his crop to his lord in exchange for protection; the artisan produced goods according to the strict regulations of the guilds, whose function it was to transmit a definite body of skills, preserve standards of quality, and eliminate competition. Similar views dominated the institutions of learning. The medical faculty of a university transmitted a body of knowledge, kept traditions pure, regulated conditions of practice, and eliminated competition. Incentive to research obviously was small in such a static society to which the idea of progress was foreign.

Conditions changed radically toward the end of the Middle Ages when feudalism began to disintegrate. The volume of trade increased, created a great demand for gold as a medium of exchange, and voyages of discovery were started to seek for it. The discovery of new continents, races, and living species were a powerful stimulus to science. Problems of navigation were acute once more; long distance voyages required larger and faster ships, and improved methods of orientation. Waterways were the chief highways of traffic. With the increasing use of firearms in warfare, the demand for copper and lead grew. Shallow deposits were exhausted, and it was necessary to dig deeper, which required more elaborate machinery and increased the dangers of mining. The development of artillery raised problems of ballistics. The works of the physicists in the 16th and 17th centuries show that practical problems of navigation and ballistics played a very important part in their studies.

A new economic order began to develop which called for free initiative and competition. A new relationship between employer and worker was gradually established. The traditional authorities were fought. The church was opposed and was "reformed." A new political philosophy of liberalism arose. As most universities preserved their medieval character and antiquated traditions until the 18th century, academies were founded and became the really active centers of scientific research.

For three centuries the battle between feudalism and capitalism went on. On one side stood a landed aristocracy and its parasites, fighting to retain its inherited privileges but losing them one after another. It was aided by the church, which since the early Middle Ages had become one of the great property owners. On the other side was a rising middle class, open-minded, progressive, fighting for political equality, producing great scientists who applied their discoveries in industry, and trading commodities on an ever-increasing scale. By the end of the 17th century the merchant class had an influential position in the British Parliament, and members of the third estate in France were permitted to acquire land of the nobility. Through the industrial revolution the middle class won its economic battle, and through the French Revolution, its political battle against feudalism. In the 19th century the bourgeoisie was in power in many countries, and where it did not actually control the state its economic power was nevertheless so great that the state had to follow its lead. The capitalistic system of production required science; and democracy appeared as the ideal form of government so long as it could be controlled by the bourgeoisie.

What are the results of these developments and what place does science occupy in a democratic society like ours? The general standard of living unquestionably has been raised considerably. Life has become safer and more comfortable. Technology has produced an infinity of most enjoyable gadgets. Science is worshipped. Whoever has something new to sell advertises it as being scientific and this is considered as the highest recommendation. A man like Einstein is highly esteemed, although most people have not the faintest idea what his contribution has been; he is worshipped in an almost mystical way as a symbol of science. But when we look under the surface we see that science actually plays an inadequate role in our society. Our system of production—the basis of our social life—produces commodities chaotically, in fits, and leads to periodic depression. Industry applies scientific principles in production but by no means freely or rationally. A new invention that may benefit society but will not be profitable to an undertaking is suppressed without hesitation. The frustrations of technology are endless. Nor is science an integral part of government activities. The statesmen as a rule know nothing about science, just as the average scientist is a perfect child in matters of economics

and politics. Although every government of an industrial commonwealth has to consult scientists, and hundreds of scientists are in the government service, whenever the government attempts to solve a problem scientifically it comes into conflict with the invested interests of a small but powerful group of the population. By the time a compromise has been reached the solution is no longer scientific. Foreign policy is still less scientific; it is impossible to make the sources of raw material available and to open the markets in a rational and scientific way. Foreign policy is a mixture of bluff, violence and compromise.

The scientist in order to make a living has to sell his labor to some institution or undertaking. In this country there are, fortunately, many academic institutions in which the scientist has the freedom to select his researches and to publish and teach what he considers the truth. But he is not free in many public schools; there are still regions in which the theory of evolution may not be taught and where textbooks must be so written that they will not offend the religious feeling of certain people. The scientist who works in industry naturally must give up much of his freedom and constantly run the risk of seeing the results of his labor suppressed for economic reasons. In other words, science today has infinitely more to give than society actually receives.

In Russia today the state is built upon the foundation of the natural sciences and economics. For the first time in history an attempt has been made to govern a country scientifically, taking advantage of all the resources of science. Production is planned scientifically on a nation-wide scale. The most important government department is the State Planning Commission which has a special university attached to it to train its staff in the sciences and economics. The Academy of Science is not merely a learned society in which distinguished scholars come together to read papers, but is the chief advisory body of the state; it surveys the natural resources of the country and devises the methods to open them up. There are no patents to prevent the universal use of inventions; new discoveries can be applied immediately all over the nation. The scientist is highly esteemed and the artificial distinction between pure and applied science has disappeared; the scientist, whether engaged in practical or theoretical work, lives in close touch with the manual laborers. The mere fact that Russia in the short period of twenty years succeeded in industrializing a backward country, and in collectivizing and mechanizing a once most primitive agriculture, demonstrates what the rational application of science can achieve. In such a society science permeates all ways of life and obviously has boundless possibilities of development.

It was encouraging to observe at the last meeting of the American Association for the Advancement of Science that the scientists are becoming aware of the part they could and should play in social affairs. In his presidential address, Professor E. G. Conklin deplored the fact that neither in human nature nor in social relations has progress kept pace with science; that knowledge and power have outrun ethics. The greatest problems that confront humanity, he pointed out, are how to promote social cooperation, loyalty to truth, justice, and a spirit of brotherhood; how to expand ethics until it embraces all mankind. These are problems for science as well as for government, education and religion. Professor Conklin's remedy is education, an education that looks to the highest development of our physical, intellectual and moral capacities. In a symposium held at this meeting, scientists praised the great achievements of science or apologized for the vile use to which they had been put. Suggestions were made to apply scientific research methods to an investigation of the causes of social unrest and war. Finally the Council of the Association passed a resolution to the effect that the Association make as one of its objectives an examination of the profound effects of science upon society; and that it extend to all other scientific organizations throughout the world, an invitation to cooperate, not only in advancing the interests of science, but also in promoting peace among nations and intellectual freedom in order that science may continue to advance and spread more abundantly its benefits to all mankind. The future will tell whether this resolution will lead to any action. Whatever organization may result from these various movements, its success or failure will depend on whether the scientists are able and have the courage to think the problems through and to draw conclusions from their observations and studies.

An appeal has been made particularly to the scientifically trained youth of the country to cooperate in the solution of social problems. This is a direct challenge to us teachers of scientific subjects who are responsible for the young generation. We here touch upon a sore spot in our educational system. Science, from the elementary school to college, is taught more or less dogmatically. The student does not feel himself stirred or challenged; his intellectual curiosity is not sufficiently aroused. Science is not presented to him in its cultural setting. A body of generally accepted knowledge, simplified and carefully digested, is transmitted to him and he accepts it as a matter of course. In the graduate school, specialists are trained who are highly efficient but totally uneducated outside of their narrow field and therefore utterly unprepared to take any part in social action. If the German academic world surrendered so readily to reactionary forces, it was largely due to the fact that it consisted of men who were specialists and nothing else. If we wish to educate a citizen able to think in terms of science, and a scientist prepared to participate in social action, we must change our teaching. One way—the most promising—is to approach the sciences not only technically but historically, philosophically and sociologically.

The author is the director of the Institute of the History of Medicine at Johns Hopkins University.—D. R.

Since there are no—or only a very few—ideal people who are entirely free from prejudice, it is sometimes of value to obtain information, especially in regard to historical data, from two different points of view.

—Wilhelm K. Röntgen.

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